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DIRECT FILTRATION OF LAKE SUPERIOR WATER FOR ASBESTIFORM FIBER REMOVAL

Black and Veatch

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Pilot plant research conducted in 1974 at Duluth, Minnesota, demonstrated that asbestiform fiber counts in Lake Superior water could be effectively reduced by municipal filtration plants. During the study, engineering data were also obtained for making cost estimates for construction and operation and both granular and diatomaceous earth (DE) media filtration plants ranging in size from 0.03 to 30 mgd. Both dual and mixed-media granular filters using alum and nonionic polymer, employing flash mix and flocculation without settling and DE filters with alum coated DE as precoat and/or body feed or with Catfloc B added to raw water, produced effluents with amphibole fiber counts below electron microscope detection limits. Turbidity was not a direct measure of fiber count, but amphibole counts were generally lowest at effluent turbidities ≤ 0.1 TU. Chrysotile removal was more difficult, but mixed media granular filtration with alum and nonionic polymer, and DE filtration with anionic polymer conditioned DE frequently reduced chrysotile fiber counts markedly. Systems for economic reasons recommended for consideration during design studies are: (1) mixed media direct filtration, 5 gpm/ft^2, multiple-stage flash mix; (2) dual media filtration, 4 gpm/ft^2, single stage flash mix; and (3) pressure DE filtration, 1 gpm/ft^2, alum conditioning of precoats and body feed, or alum conditioning of precoat only, and cationic polymer fed to raw water.

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DIRECT FILTRATION OF LAKE SUPERIOR WATER FOR ASBESTIFORM FIBER REMOVAL

By

Black & Veatch, Consulting Engineers
Kansas City, Missouri 64114

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment -- air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

This report presents the results obtained and conclusions drawn from pilot plant filtration research for the removal of asbestiform fibers from drinking water. The appendices, which are available separately, present detailed information on water quality, pilot plant equipment and operation, individual filter run data, asbestiform fiber and amphibole mass concentrations in raw and filtered water, and diatomite filter optimization.

Arrangements for performance of this research were made through an interagency agreement between EPA Region V and the Corps of Engineers, St. Paul, Minnesota.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

Pilot plant research conducted in 1974 at Duluth, Minnesota, demonstrated that asbestiform fiber counts in Lake Superior water could be effectively reduced by municipal filtration plants. During the study, engineering data were also obtained for making cost estimates for construction and operation of both granular and diatomaceous earth (DE) media filtration plants ranging in size from 0.03 to 30 mgd.

Both dual and mixed-media granular filters using alum and nonionic polymer, employing flash mix and flocculation without settling, and DE filters with alum coated DE as precoat and/or body feed or with Catfloc B added to raw water, produced effluents with amphibole fiber counts below electron microscope detection limits. Turbidity was not a direct measure of fiber count, but amphibole counts were generally lowest at effluent turbidities ≤ 0.1 TU. Chrysotile removal was more difficult, but mixed media granular filtration with alum and nonionic polymer, and DE filtration with anionic polymer conditioned DE frequently reduced chrysotile fiber counts markedly.

Systems for economic reasons recommended for consideration during design studies are:

1. Mixed media direct filtration, 5 gpm/ft^2, multiple-stage flash mix.

2. Dual media filtration, 4 gpm/ft^2, single stage flash mix.

3. Pressure DE filtration 1 gpm/ft^2, alum conditioning of precoats and body feed, or alum conditioning of precoat only, and cationic polymer fed to raw water.

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SECTION I

CONCLUSIONS

GENERAL

1. The raw water turbidity experienced at the Duluth Lakewood Intake during the pilot studies ranged from 0.4 to 6.3 TU, but was less than 1.0 TU 90 per cent of the time.

2. Heavy rainfall and high winds resulted in increases of suspended solids, turbidity, and bacteriological counts as well as changes in temperature in the Duluth raw water; however, only high winds, generally from the east and northeast, resulted in increases in amphibole fiber concentrations.

3. A general link was evident between the turbidity and the suspended solids concentration of the raw water from the Duluth Lakewood Intake.

4. The data indicate a close connection in turbidity readings utilizing a Hach 2100A laboratory turbidimeter, a Hach 1720 in-line turbidimeter, and a Monitek in-line turbidimeter.

5. No discernible tie was evident between the Duluth raw water turbidities and the asbestiform fiber levels.

6. At finished water turbidities of less than 0.1 TU, the amphibole fiber count and mass determinations were usually below the detection limits of the analytical method used.

7. A general association was indicated between the NWQL amphibole mass concentration and the ORF amphibole fiber counts in the Duluth raw water.

8. No relationship was observed between the counts of the amphibole and the chrysotile fibers in the Duluth raw water.

9. Proposed treatment facilities are capable of meeting the new Federal Safe Drinking Water Act standards which establish a maximum turbidity in drinking water of 1.0 TU.

TREATMENT FOR ASBESTIFORM FIBER REMOVAL

Granular Media Filtration

Based on achieving BDL or near it, 32 of 34 MM-2 (granular) runs and 21 of 23 MM-1 runs were successful for amphibole removal. Only 8 of 34 MM-2 runs and 2 of 23 MM-1 runs were successful for chrysotile removal.

Diatomaceous Earth Filtration

For the ERD (pressure) runs, 19 of 27 were successful for amphibole removal but only 4 of 27 were successful for chrysotile removal. Vacuum DE filtration (BIF) was not found suitable for treating the raw water being tested.

TREATMENT FOR TURBIDITY REMOVAL

Granular Media Filtration

1. Within the range of raw water turbidities experienced during the pilot study, the effluent turbidity, length of filter run, sludge production, and asbestiform fiber removal were more affected by the choice and amount of chemicals than by the raw water turbidity.

2. Alum was a more effective coagulant than ferric chloride in the Duluth raw water, producing lower effluent turbidities and longer filter runs.

3. Of the polymers tested in the pilot study, a nonionic polymer, 985N, was the most effective in preventing turbidity breakthrough.

4. Resistance to turbidity breakthrough was greater with two-stage flash mixers than with in-line mixers. Both systems were more effective in terms of filter run length and turbidity removal than single-stage mixing.

5. Sedimentation prior to filtration increased filter run length in proportion to the amount of solids removed in the sedimentation process, but did not increase fiber removal.

6. A sludge production of approximately 0.03 pound per 1000 gallons and a backwash volume of approximately 1.4 per cent of the treated water resulted from an average granular media filter run.

7. Amphibole fiber removal accomplished by the tri-media filter exceeded that accomplished by the dual media filters and the DE filters.

8. Tri-media filtration with two stage flash mixing resulted in the lowest chemical costs.

9. For raw water conditions similar to those experienced during the pilot studies, granular filters operated under positive head conditions would minimize air binding of the filter.

10. Granular filtration rates approaching 352 m^3/m^2 day (6 gpm/ft^2) were effective in the removal of turbidity and amphibole fibers.

11. The amphibole content of settled backwash wastewater was found to be the same order of magnitude as that of the raw water.

Diatomaceous Earth Filtration

1. The vacuum DE unit was affected more adversely by the release of dissolved gases from the raw water than the pressure DE unit, resulting in turbidity breakthrough and passage of DE through the filter septum.

2. Total precoat weights of 0.731 to 0.974 kilogram per square meter (0.15 to 0.2 pound per square foot) of filter area were required to eliminate high effluent turbidity and to maintain stability in the precoat.

3. A change in grade of DE in the body feed application from fine to coarse resulted in an increase in the filter run length and higher effluent turbidities.

4. The rate of head loss buildup and length of filter run in the DE units were affected more by the type of precoat and the type and amount of DE and chemicals in the body feed process than by the turbidity of the raw water.

5. A medium grade precoat and a fine grade body feed were most effective in turbidity and asbestiform fiber removal.

6. For the Duluth raw water, two treatment conditions, alum and soda ash added to the precoat with a cationic polymer introduced to the raw water, and an anionic polymer added to the precoat, were most effective in turbidity and asbestiform fiber removal.

7. Although an optimum flow rate of 94 m^3/m^2 day (1.6 gpm/ft^2) is theoretically obtainable, the rate of 60 m^3/m^2 day (1.0 gpm/ft^2) as employed in the pilot study will result in substantial turbidity and asbestiform fiber removal.

SECTION II

RECOMMENDATIONS

GENERAL

1. Quality control of the filter operation should be based on maintaining a finished water having a turbidity not greater than 0.1 TU.

2. In-line turbidimeters should be used for continuous monitoring of the raw and finished water turbidity.

3. Electron microscope analysis for asbestiform fiber counts should be performed periodically on raw and finished water samples to check on the effectiveness of the treatment processes for fiber removal.

4. Analysis for amphibole mass by X-ray diffraction in raw and finished water should be performed more frequently than electron microscope analysis due to the lower costs and more rapidly obtainable results involved.

5. Costly and time-consuming electron microscope analysis for asbestiform fiber counts should be replaced by improved analytical techniques as soon as they become available.

6. For large capacity plants, granular filtration of Lake Superior water is recommended over diatomaceous earth filtration. For small plants, diatomaceous earth filtration should also be considered.

GRANULAR MEDIA FILTRATION

1. Two stage flash mixing followed by flocculation is recommended for conditioning the raw water prior to filtration.

2. A positive head tri-media filter designed to operate at a rate of 290 m^3/m^2 day (5 gpm/ft^2) at design flow is recommended.

3. For treatment of Lake Superior water at the Duluth Lakewood Intake, alum at 12-20 mg/l and 985N or an equivalent nonionic polymer at 0.05 mg/l is recommended when the raw water turbidity is near 1.0 TU.

4. Although sedimentation is not required for fiber removal, presedimentation could be used to reduce the solids loading to the filters and to extend filter run lengths.

5. Provision should be made for the introduction of polymer to the flash mixers, the flocculation chambers, the filter beds, or to any combination of the three locations. In addition, provision for the addition of a second polymer should similarly be made as a potential aid in chrysotile removal.

6. Backwash wastewater should be discharged to a sludge lagoon, with return of the supernatant to the treatment plant.

DIATOMACEOUS EARTH FILTRATION

1. For the conditions experienced during the pilot studies, pressure DE filtration is recommended with provisions for addition of chemical aids to the precoat, the body feed, and the raw water.

2. The DE filters should be designed for a flow rate of approximately 60 m^3/m^2 day (1.0 gpm/sq ft^2).

3. A medium grade DE at approximately 0.974 kilogram per square meter (0.2 pounds per square foot) of filter area coated with alum at 0.01 g/g of DE and soda ash at 0.005 g/g of DE and a cationic polymer at 0.5 mg/l added to the raw water or an equal grade and amount of DE coated with an anionic polymer at 0.00005 g/g of DE should be used for precoating for treatment of Lake Superior water at the Duluth Lakewood Intake.

4. A fine grade of DE at a rate of 20 to 30 mg/l should be used for body feed for treatment of Lake Superior water at the Duluth Lakewood Intake.

SECTION III

INTRODUCTION

PURPOSE OF STUDY

The pilot filtration study was conducted to determine which of the filtration systems studies was most effective in the removal of asbestiform fibers, and to obtain for each system the necessary data for design of a full-scale water treatment plant. Data to be obtained included raw and filtered turbidities, asbestiform fiber removal efficiencies, length of filter run, rate of head loss buildup, and sludge produced per 1,000 gallons (gal) of water treated.

BACKGROUND

Prior to initiation of the pilot filtration study, little was known about the removal of asbestiform fibers from water. However, studies conducted by the Corps of Engineers did indicate a substantial portion of the asbestiform fibers could be removed from the water using pressure diatomaceous earth (DE) filters. In addition, studies at the U. S. Environmental Protection Agency (EPA) laboratory in Cincinnati indicated that granular filters could also effectively remove much of the asbestiform fibers from the water. The selection of granular and DE filters for testing during the pilot filtration study was made on the basis of the work conducted by the U. S. Army Corps of Engineers and the EPA.

SCOPE OF STUDY

During the period from April through September, 1974, four pilot filter units were operated in Duluth, Minnesota, on Lake Superior water. The primary goal of the pilot filtration study was the investigation of the ability of various filtration systems to remove the asbestiform fibers and turbidity found in the water supplies of the Duluth-Superior-Cloquet area, with emphasis on removal of fibers and turbidity from the raw water obtained at the Lakewood Intake in Duluth, Minnesota. Filtration processes investigated included granular filtration, pressure DE filtration, and vacuum DE filtration. The study was originally scheduled to be completed after a period of 4 months, but results obtained during this period indicated further study would be beneficial. The study was therefore extended for 5 weeks, with additional variables in operation investigated, especially to increase the removal of chrysotile fibers. A total of 227 granular filter runs and 228 DE filter runs were conducted. Limitations of time and money prevented study of other methods of water treatment which might have been considered.

Variables studied during the pilot plant operation are summarized below:

ELEMENTS OF STUDY

Granular Media Filtration

1. Filtration with and without prior sedimentation.
2. Effectiveness of combinations of iron salt and polymers and aluminum salt and polymers.
3. Dual media versus tri-media filter bed.
4. Effect of filtration rate.
5. Rate of head loss buildup.
6. Sludge production.
7. Effect of seasonal conditions.
8. Effect of raw water turbidity on filter performance.
9. One-stage versus two-stage flash mixing.

10.* Flash mixing chambers versus in-line mixers.

11.* Techniques for increased removal of chrysotile as well as amphibole fibers.

12.* The effect of higher raw water algal counts on filter performance (no algal blooms occurred).

Diatomaceous Earth Filtration

1. One-step versus two-step precoating.
2. Effect of body feed concentration.
3. Addition of chemical aids to precoat and/or body feed.
4. Rate of head loss buildup.
5. Sludge production.
6. Effect of seasonal conditions.
7. Effect of raw water turbidity on filter performance.

* Variables studied during the 5 week extension.

8.* Techniques for increased removal of chrysotile as well as amphibole fibers.

9.* The effect of higher raw water algal counts on filter performance.

10.* Generation of adequate data for input to the POPO computer program.

* Variables studied during the 5 week extension.

SECTION IV

EQUIPMENT DESIGN, INSTALLATION, AND OPERATION

GENERAL

The pilot filtration study was conducted with two granular filters and four DE filters installed at the Lakewood Pumping Station in Duluth, Minnesota. The granular filters were a skid-mounted and a trailer mounted "WATER-BOY" unit as manufactured by Neptune MicroFLOC, Incorporated, Corvallis, Oregon. The DE filters were two pressure DE units supplied by the Corps of Engineers and two vacuum DE units as manufactured by the BIF Corporation, Providence, Rhode Island.

RAW WATER SOURCES

With the exception of three runs on the MM-2 units, all runs on the pilot filtration units were made using the Lakewood wetwell as the raw water source. The intake of the Lakewood Pumping Station extended approximately 1,500 ft out into Lake Superior and was about 70 ft below the surface of the lake. Suction hoses were placed directly in the wetwell and raw water was pumped to each of the filter units so that the raw water supplied to the units was the same as that being supplied to the City of Duluth.

Raw water from the Cloquet Pipeline Intake was used for three runs on the MM-2 units. The Cloquet raw water was transported from the Cloquet raw water pumping station on Minnesota Point to the Lakewood Pumping Station in a 4,800 gal tank truck. After the truck arrived at Lakewood, the suction of one of the pilot plant raw water pumps was connected to the discharge from the tank truck and the water pumped to the MM-2 unit.

PERSONNEL

The operation of the pilot filtration systems was conducted by three operators and a field engineer. The pilot filters were operated in 8-hour shifts, 24 hours a day, 5 days a week for a period of 5 months extending from April 19, 1974 to September 20, 1974. The study was conducted in three phases:

1. A preliminary test phase to train the operators, develop testing and data recording procedures, and gain plant operating experience.

2. A treatment efficiency phase to determine which treatment methods gave promise of effectively removing asbestiform fibers from the raw water.

3. An "optimum-design" phase. The operation of the DE filters during this phase was conducted to determine filter cake resistance measurements necessary for optimum design of DE filters to provide least cost of filtration of Lake Superior water. The granular filters were operated during this phase with several variations in the physical set-up of the filter systems to determine the best process scheme for asbestiform fiber removal.

AMBIENT CONDITIONS

To determine if any relationship existed between ambient conditions and the quality of the raw water at the Lakewood Pumping Station, daily records were maintained on temperature, wind velocity and direction, precipitation, and lake level. The daily temperatures and wind velocities and directions were obtained from records kept by the operators at the Pumping Station. The Pumping Station records are not official, but because of the wide discrepancy between weather conditions at the Pumping Station and the National Weather Service Station, it was decided that the unofficial records would better represent the conditions at the Pumping Station Intake. No record of precipitation was kept at the Pumping Station. Therefore, official National Weather Service data were used for precipitation values. Lake level data were obtained from the Corps of Engineers station in Duluth, and are based on International Great Lakes datum. Records of temperature, wind velocity and direction, precipitation, and lake level are presented in Appendix A-1.

A record was also maintained of the Lakewood raw water pumping schedule. This record is presented in Appendix A-2. All data in the tables refer to Pump No. 2 as this was the only raw water pump which the City operated during the course of the pilot filtration study.

GRANULAR UNITS

Because the turbidity of Lake Superior water is generally low and in such circumstances direct filtration has been found to be successful for turbidity removal, this process was tried for fiber removal. In direct filtration, water is conditioned with an inorganic coagulant and polymer and filtered (usually through dual or mixed media) without sedimentation. Selection of the particular granular media used was based on the wide and successful experience with the media chosen.

Size and Type

The two granular units used in the filtration study were designated as MM-1 and MM-2. The only difference in the basic set-up of the two filters was in the size of the settling basins. MM-1 had a settling basin with a volume of 1,708 liters (451 gal) and MM-2 a settling basin with a volume of 693 liters (183 gal) allowing for approximately 30 centimeters of freeboard at the design rate utilized. Dimensions of each of the granular units are presented in Table 1. Further details appear in Appendices B-1 and B-2.

TABLE 1. DIMENSIONS OF UNIT PROCESSES OF GRANULAR FILTERS

Pilot Unit	Length cm	Width cm		Depth cm
MM-1				
Mixing chamber	62.2	29.5		182.9
Flocculation chamber	65.5	62.2		182.9
Sedimentation chamber	154.2	91.2	Varied	163 to 183
Filter chamber	62.7	62.2		182.9
Clearwell	–	137.9[a]		152.4
MM-2				
Mixing chamber	62.0	29.2		184.2
Two-stage mixing chamber[b]	–	–		–
Kenics mixers	52.7	5.08[a]		–
Flocculation chamber	62.0	61.5		184.2
Flocculation chamber[c]	152.4	30.0	Varied	157 to 178
Sedimentation basin[c]	152.4	30.0	Varied	157 to 178
Filter chamber	62.2	62.0		184.2
Clearwell	152.4	91.4		177.8

[a] Diameter rather than width.

[b] 208 liter (55 gal) drum.

[c] Used for flocculation on all runs except Run 140.

Mixing and Settling Variations

A flow diagram of the MM-1 (granular) unit is presented on Figure 1. Raw water entered the flash-mixing chamber of the unit where the coagulant was added. Detention time in the mixing chamber was 5.1 minutes (min) at a nominal flow rate of 87 cubic meters per day (m^3/day), or 16 gallons per minute (gpm).

Calculation of all detention times was based on flow rates and unit volumes. From the mixing chamber, the water entered the flocculation chamber where the polymer was added. With sedimentation, the polymer was added at the entrance to the sedimentation chamber (Figure 1). Detention time in the flocculation chamber was 12.3 min. After flocculation, the water was discharged either into the sedimentation basin or directly onto the filter, depending upon which mode of operation was being used. A dual media filter bed with an effective surface area of 0.37 square meter (m^2), or 4 square feet (ft^2) was used in all runs conducted with the MM-1 unit. Flow through the filter bed was maintained at a constant rate by a float valve located on the effluent discharge line. A water meter was installed in the effluent line to determine the rate of flow through the unit and the total volume of water treated during each run.

Sedimentation ahead of the filter was provided by removal of a bypass line and installation of tube settlers in the sedimentation chamber. The tube settlers were hexagonal-shaped, installed on a slope of 5 degrees, with a diameter of 2.54 cm (1 in) and a length of 1.2 meters (4 ft). A detention time of approximately 28 min was provided in the sedimentation chamber at a nominal flow rate of 87 m^3/day (16 gpm).

Flow diagrams of the MM-2 (granular unit) are presented on Figures 2 and 3. Raw water was introduced into one of several points described below for chemical mixing:

1. A flash mixing chamber.
2. A sequence of two 208 liter (55 gal) external flash mixing drums.
3. A sequence of Kenics in-line static mixers external to the unit.

The flash mix chamber provided a detention time of 5.0 min at a filter rate of 87 m^3/day (16 gpm). Flow from the flash mix chamber was discharged into a flocculation chamber, with a detention time of 10.3 min, where the polymer was added.

For the sequential backmix system, flash mixing occurred in two steps in two 208 liter (55 gal) drums. The primary coagulant was added at Point C, (Figure 3)and the polymer was added at Point D (Figure 3). At a filter rate of 87 m^3/day (16 gpm), the theoretical detention time was 2.8 min in the first drum and 2.2 min in the second drum. When three treatment chemicals were used in sequence, the third was added at Point D (Figure 2).

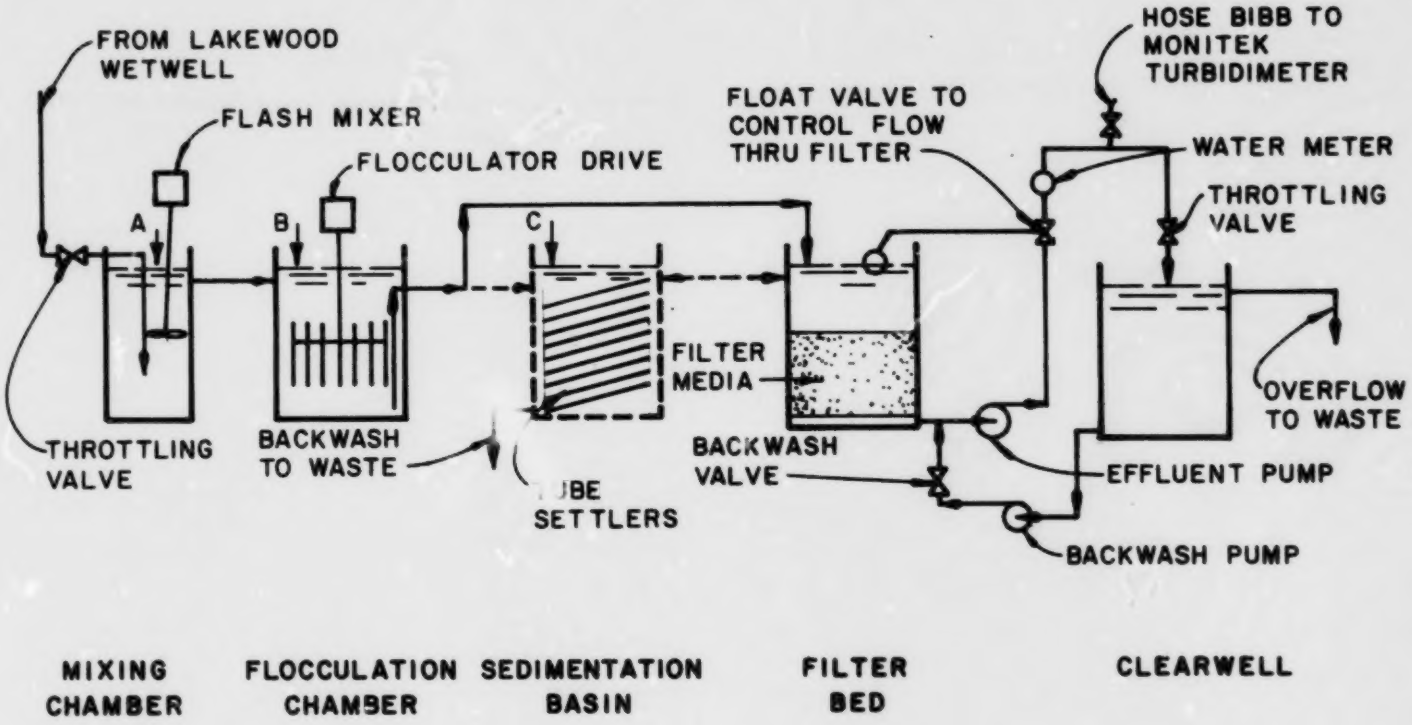

FIGURE 1 . FLOW DIAGRAM FOR MM-1.

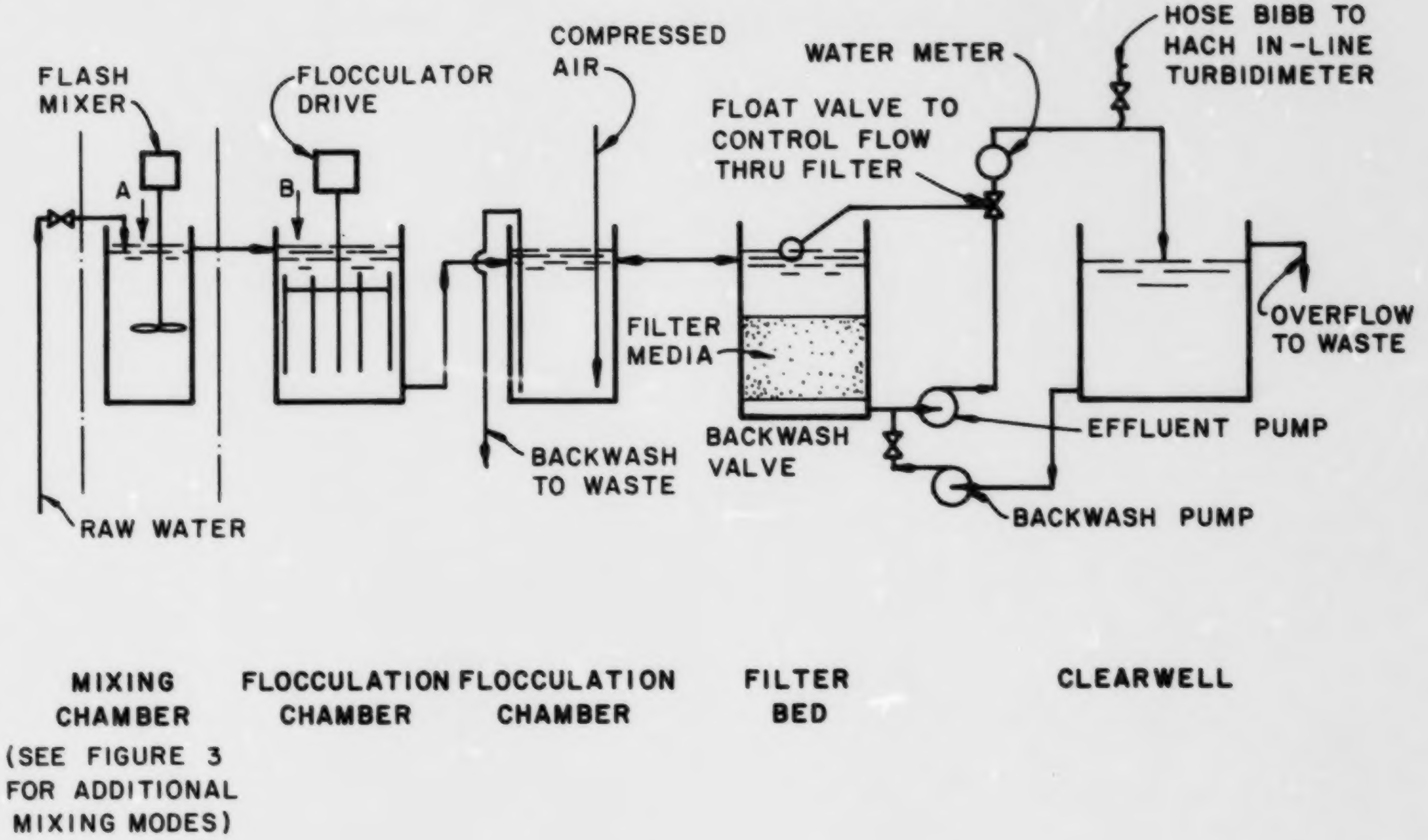

FIGURE 2 . FLOW DIAGRAM FOR MM-2.

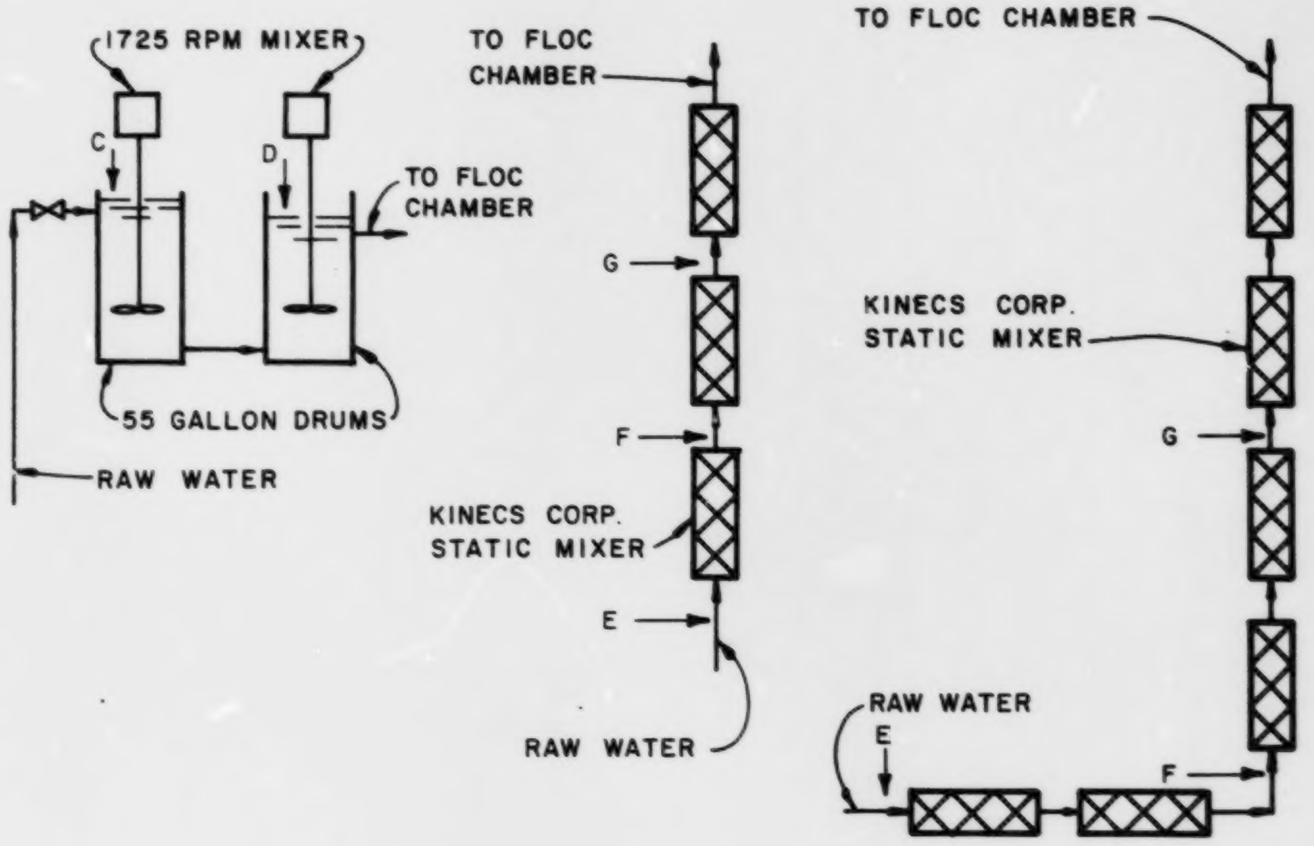

FIGURE 3 . ALTERNATIVE MIXING MODES FOR MM-2.

With the sequential in-line mixing, shown on Figure 3, a combination of three or six 5.08 cm (2 in) diameter Kenics static mixers were used. Provision was made for adding up to three different treatment chemicals at Points E, F, and G. Mixing of water and chemical occurred in either one or two mixers before the next chemical was added. At a filter flow rate of 87 m^3/day (16 gpm), the detention time in each static mixer module was 1.1 seconds.

Flow from the mixing portion of the process was discharged into a flocculation chamber, with a detention time of 10.3 min at a filter rate of 87 m^3/day, (16 gpm). An additional 11.4 min of flocculation was provided by removing the tube settlers from the sedimentation chamber of the MM-2 unit and bubbling air up through the flow as it passed through the chamber.

From the sedimentation chamber, the flow was discharged onto the filter. A dual media filter bed was used in 76 runs and a tri-media filter bed in 64 runs conducted with the MM-2 unit. The filter bed had an effective surface area of 0.37 m^2 (4 ft^2). Flow through the filter was maintained at a constant rate by a float valve located on the effluent discharge line. A water meter was installed in the effluent line to establish filter flow rates and to determine the total volume of water treated during each run.

Filtration Rates

All runs on the MM-1 unit were conducted at a flow rate of approximately 232 cubic meters per square meter day (m^3/m^2 day), or 4 gallons per minute per square foot (gpm/ft^2).

Most of the runs on the MM-2 unit were conducted at a flow rate of approximately 232 m^3/m^2 day (4 gpm/ft^2). However, to determine the effects of flow rate on the performance of the filter, 14 runs were conducted at a flow rate of approximately 290 m^3/m^2 day (5 gpm/ft^2), 3 runs at about 116 m^3/m^2 day (2 gpm/ft^2), and 22 runs at approximately 350 m^3/m^2 day (6 gpm/ft^2).

Media Description

The results of a sieve analysis on the various medias and the composition of the dual and tri-media beds used during the pilot study are given in Table 2.

TABLE 2. SIEVE ANALYSIS OF FILTER MEDIA[a]

Media	Effective Size mm	Uniformity Coefficient	Media Thickness Dual Media cm	Media Thickness Tri Media cm
Anthracite	1.10	1.60	53.3	41.9
Brady sand	0.42	1.52	22.9	22.9
Fine illmenite	0.22	1.66	–	11.4
Coarse illmenite	1.02	1.55	–	3.8
Very coarse illmenite	1.75	2.06	–	3.8

[a] Analysis performed by Neptune MicroFLOC, Incorporated.

The dual media bed was used for all runs on MM-1 and 76 runs on MM-2 and was placed directly on the carborundum filter bed supports provided with each of the granular units. The tri-media bed was used for the last 64 runs on the MM-2 unit. To insure that none of the fine illmenite would pass through the carborundum support, two coarser sizes of illmenite were placed on the carborundum support prior to installation of the bed.

The dual media beds were installed under the supervision and direction of a representative of Neptune MicroFLOC, Inc. The tri-media bed was installed by the field engineer with assistance from the pilot plant operators. The placement of the beds was accomplished by adding an excess of the bottom layer of media, backwashing the filter, skimming about one-half the excess media off, backwashing again and skimming off the remainder of the excess media. This procedure was repeated for each media.

Chemical Additions

Alum and ferric chloride ($FeCl_3$) were used as the primary coagulants in the testing of the granular filters. The coagulant solutions were mixed daily at the pilot plant site to a 1.19 per cent solution strength using dry chemicals and raw water from the Lakewood Intake.

The polymers used in the pilot filtration study were selected partially on the basis of availability and partially on the basis of jar tests conducted at the Lakewood laboratory. The polymers utilized in the filtration study are presented in Table 3.

TABLE 3. POLYMERS UTILIZED IN FILTER RUNS

Polymer[a]	Type	Manufacturer	Home Office
A-23	Anionic	Dow	Midland, Mich.
847A	Anionic	Cyanamid	Chicago, Ill.
Separan NP-10	Weak Anionic	Dow	Midland, Mich.
Catfloc B	Cationic	Calgon	Pittsburg, Pa.
C-31	Cationic	Dow	Midland, Mich.
573C	Cationic	Cyanamid	Chicago, Ill.
985N	Nonionic	Cyanamid	Chicago, Ill.
N17	Nonionic	Dow	Midland, Mich.

[a] Each of these polymers is approved by the EPA for potable water use.

The liquid polymers were generally mixed for at least 30 min before use and the powdered polymers were mixed in excess of 1 hour before use.

Backwashing

Backwashing of the granular units was initiated for one of two reasons, either excessive head loss through the filter or excessive effluent turbidity. If effluent quality was satisfactory, the filter was backwashed whenever the head loss through the filter exceeded 8 ft of water. Effluent quality controlled initiation of the backwash cycle whenever the turbidity exceeded 1.0 TU or the turbidity of the raw water, whichever was lower, or whenever it became evident that turbidity breakthrough had occurred. Turbidity breakthrough was evidenced by a sudden and continuous rise in effluent turbidity readings.

A water only backwash with no surface wash was used for cleaning the granular unit filter bed. To determine the amount of backwash water used and the rate of backwashing, the length of backwash, and the level of water in the backwash tank before and after each backwash cycle were recorded. Backwashing rates and length of backwash varied, but were usually about 755 m^3/m^2 day (13 gpm/ft^2) and 7 min respectively.

DIATOMACEOUS EARTH UNITS

Four DE filter units were installed at the pilot plant site, two vacuum filters and two pressure filters. Both vacuum and pressure units were installed to determine if release of dissolved gases under vacuum conditions would be detrimental to the filtration process. Although two vacuum filters were installed, only one was used for the pilot study, with the second filter provided as a standby unit. The vacuum DE filter was designated as the BIF unit. The pressure DE filters were designated ERD-1 and ERD-2, but the two pressure filters were identical and all data and discussion will be presented under the heading ERD. The dimensions of the units are given in Table 4.

TABLE 4. DIMENSIONS OF DE UNITS

Pilot Unit	Length cm	Width cm	Depth cm
BIF			
Filter section	78.7	20.32	Varied 72.4 to 76.2
Raw water tank	–	68.6[a]	92.7
DE slurry or polymer tank	–	35.0[a]	50.8
ERD			
Water treatment section	–	Varied 67.3 to 221.0[a]	147
Filter section	–	Varied 7.6 to 40.6[a]	137
DE slurry or polymer tank	–	61.0	91

[a] Diameter rather than width

Vacuum Unit

A flow diagram of the BIF unit is presented on Figure 4. Raw water entered the mixing chamber where chemical or body feed additions, if any, were made and mixing was accomplished. The water level in the mixing chamber was controlled by a float valve installed on the influent raw water line. Dry body feed was added by a helix feeder. If alum-coated body feed was being used, a DE slurry was mixed in a slurry tank and fed to the mixing chamber. From the mixing chamber, the water flowed into the filter section of the unit where the water passed through the filter elements due to suction from the effluent pump, and was discharged into the waste sump. The filter had an effective surface area of 0.93 m^2 (10 ft^2). A water meter was installed in the effluent line to set flow rates and determine the total amount of water treated during each run.

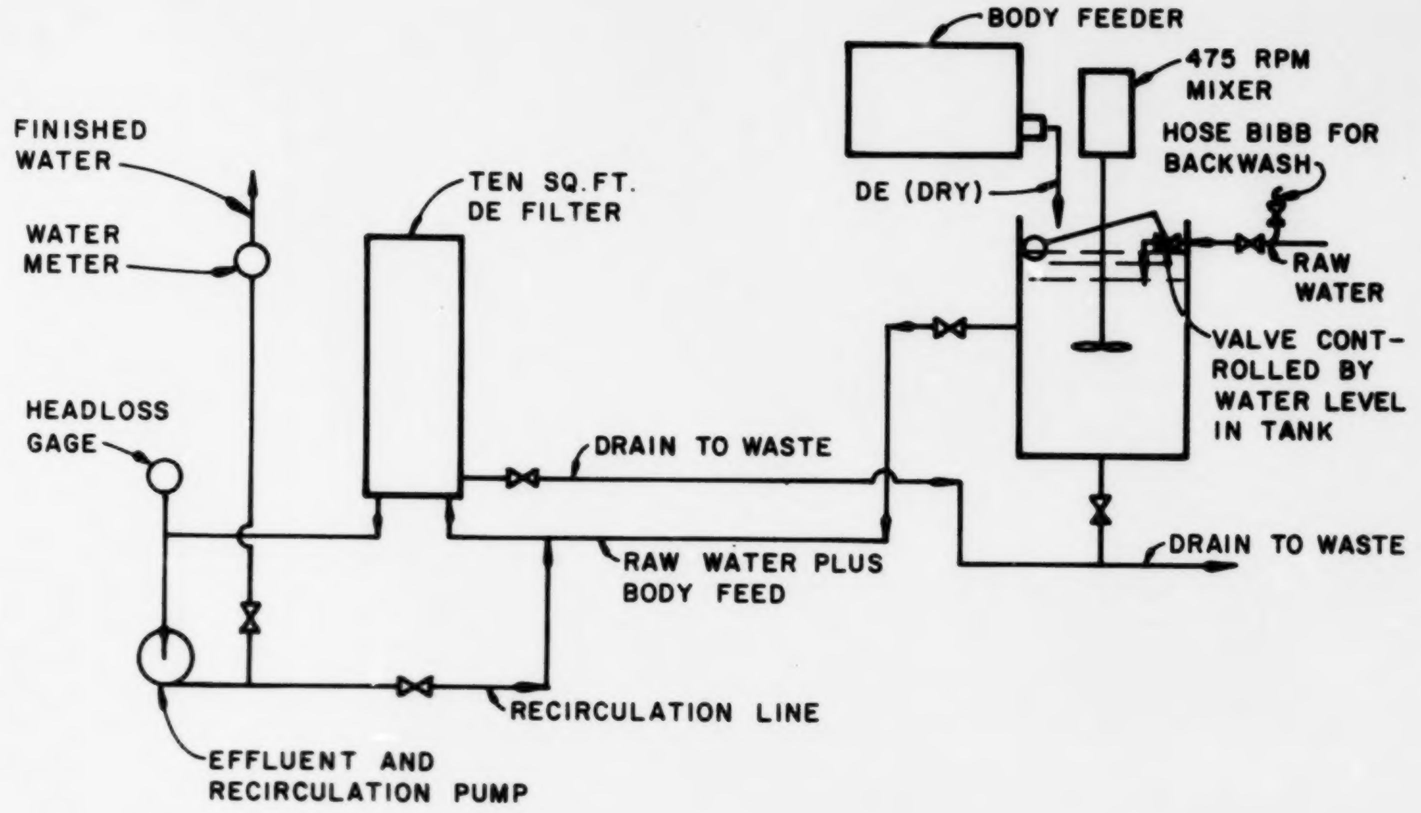

FIGURE 4 . FLOW DIAGRAM FOR BIF (ALT. I)

Pressure Unit

A flow diagram of the ERD unit is presented on Figure 5. The unit consisted of a water treatment section, a filter section, and a drain tank. The water treatment section was designed to remove organic and suspended matter in the raw water to a level suitable for further treatment in the filter section. However, the quality of the raw water at the Lakewood Pumping Station was such that treatment of the water ahead of the filter section was not considered necessary. Therefore, no coagulants were added in the water treatment section. Because of the piping configuration of the unit, water did flow through this section.

Each DE filter was a two-part cylinder containing six cylindrical elements, with each element having an effective surface area of 0.15 m^2 (1.67 ft^2), providing a total filtration area of 0.9 m^2 (10 ft^2) per filter. Each filter was equipped with gages for indicating influent and effluent pressure, a precoat funnel, an air release valve, and a rate of flow controller in the effluent discharge line.

Filtration Rates

All runs on the BIF and ERD units were made at a flow rate of approximately 58 m^3/m^2 day (1 gpm/ft^2), using raw water from the Lakewood Intake, and were made without sedimentation prior to filtration.

Precoat Methods

Although the ERD unit is a pressure type filter and the BIF unit a vacuum type filter, the principle of operation for the units is essentially the same. DE filtration as conducted during the pilot filtration study consists of three basic steps:

1. Precoating
2. Filtration
3. Backwash

The purpose of the precoat is to give immediate clarity and to prevent the filter septa from becoming clogged by impurities contained in the raw water. Precoating is accomplished by circulating a slurry of DE through the filter septa. Since most of the DE particles are larger than the openings in the filter septum, they form a precoat by bridging these openings. After the precoat is formed on the filter septa, the filtration process is begun by positioning appropriate valves on the unit from the recirculation to the filter position, and initiating body feed to the flow of water. This normal precoat procedure was altered somewhat when it was

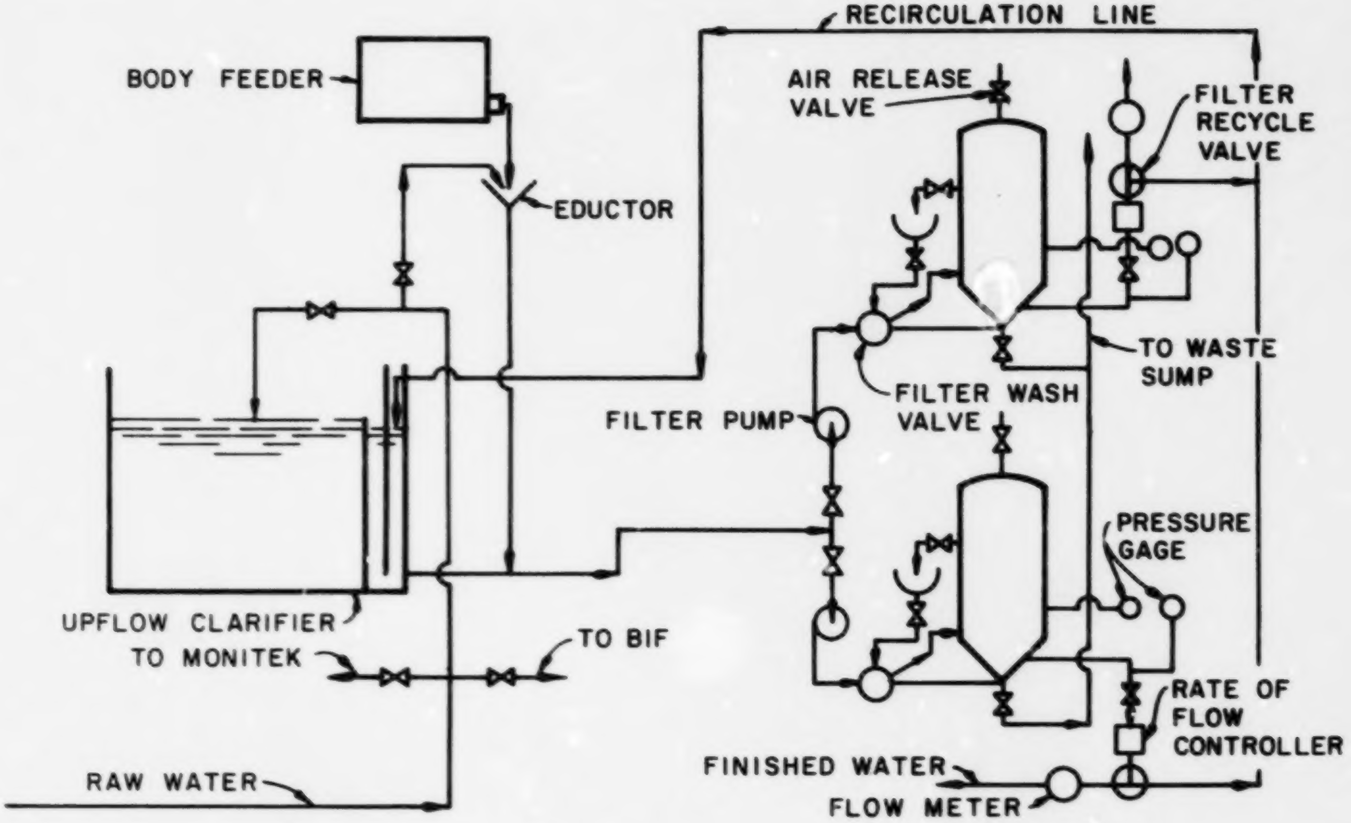

FIGURE 5 . FLOW DIAGRAM FOR ERD (ALT. I) discovered early in the research through analysis that a portion of the DE was passing through the filter into the treated water. A two-step precoating procedure was initiated in an effort to eliminate the DE bleed-through. The procedure when precoating in two steps was similar to that used when precoating in one-step except that two DE slurries were mixed, one using a coarse DE and one using a fine DE. After mixing the two slurries and filling the filter section with raw water, the recirculation pump was started and the coarse DE slurry poured into the filter section. The unit was placed in recirculation until the water cleared and then the fine DE slurry was poured into the filter section. The unit continued to recirculate until the water once again cleared, at which time the recirculation valve was closed and the effluent valve opened to the position giving the desired flow through the filter unit. Bleed-through of DE through the filter septa was discovered during the first week of testing. The two-step precoat method utilized was successful in eliminating the bleed-through problem.

Body Feed

The purpose of the body feed is to maintain the permeability of the filter cake. The amount of body feed added is dependent upon the concentration of suspended solids contained in the raw water and must be carefully controlled to achieve the maximum filter cake permeability. Too much DE relative to the suspended solids concentration will add excessive thickness to the filter cake and reduce the cake permeability. Too little DE will not sufficiently offset the effect of the raw water suspended solids, and will either allow breakthrough of solids or result in a reduction in the filter cake permeability.

DE Filter Aids

DE filter aids are produced by several manufacturers in several grades. Table 5 lists the filter aids utilized in the pilot filtration study. The table lists the trade name of filter aid grades from several manufacturers that are "equivalent". Filter aids are considered "equivalent" when they produce approximately the same flow rate and clarity under the same operating conditions.

TABLE 5. EQUIVALENT DE FILTER AIDS

Brand Name	Mean Particle Size µm	Structure	Equivalent Filter Aid
Celatom FW-6[a]	6	Flux	Celite 512[b]
		Calcined	Special Speedflow[c]
Celatom FW-12[a]	8	Flux	Hyflo Super Cel[b]
		Calcined	Speedplus[c]
Celatom FW-20[a]	12	Flux	Celite 503[b]
		Calcined	Speedex[c]
Celatom FW-50[a]	15	Flux	Celite 535[b]
		Calcined	4200[c]
Celatom FW-60[a]	19	Flux	Celite 545[b]
		Calcined	4500[c]

[a] Manufactured by Eagle-Pitcher Industries, Inc.

[b] Manufactured by Johns-Manville Products Corporation.

[c] Manufactured by Dicalite Division Grefco, Inc.

DE Conditioning

Modifications made in the operation of the DE units during the course of the pilot filtration study to enhance asbestiform fiber removal included:

1. Addition of chemical aids to the precoat
2. Two-step precoating
3. Addition of chemical aids to the body feed
4. The addition of polymer along with body feed into the raw water

Runs made with a single precoat and no chemical aids in the precoat or body feed did not have satisfactory finished water turbidities. In an attempt to lower the effluent turbidities, an anionic or cationic polymer was added to the precoat. The precoat procedure when polymer was used in the precoat was unchanged from the above except that polymer was added to the DE slurry prior to precoating. The anionic polymer was added to the DE slurry as a 0.01 per cent solution and from 0.00001 to 0.00005 gram of polymer per gram of DE (g/g DE) was added. The cationic polymer was added as a 0.1 per cent solution and from 0.0003 to 0.0006 g/g DE was added.

Several two-step precoats were made using a chemical aid in both the coarse and fine steps. Polymers were added to the precoats in the same manner as when a single precoat was used. Alum was added to the precoats as a 5 per cent solution and from 0.01 to 0.11 g/g DE was added. In addition, whenever alum was added to the precoats, sufficient soda ash, partly purified sodium carbonate, was added to prevent depression of the pH to a value lower than 7.0. To allow time for alum coating of the DE, the alum, soda ash, and DE were added to 3.78 liters (1 gal) of water, the mixture was stirred, restirred after 5 min of quiescent settling, again restirred after another 5 min of quiescent settling, and then poured into the filter section. All other steps in the precoat procedure were the same as previously described in this section.

The use of chemical aids in both precoats sometimes resulted in plugging of the filter septa. To prevent plugging, the chemical aid was added only to the second precoat, with the first precoat being used as a protective coat for the filter septa.

Backwashing

As the permeability of the filter cake decreased, the head loss through the filter increased until it reached a point where the unit must be backwashed. To control the operation of the filters, the turbidity of the raw and finished water and the head loss through the filters were recorded hourly for each of the DE units. The total head loss through the filter which could be tolerated varied due to several factors, with one of the more important being type of filter system used, i.e., a pressure or a vacuum system. A pressure system could be operated at a much higher pressure differential than a vacuum system. During the backwashing of the unit, the DE, including the precoat, was completely flushed from the filter septa. The unit was then ready for a subsequent precoat-filtration-backwash cycle.

Backwashing of the units was initiated for one of three reasons:

1. Excessive head loss through the filter
2. Excessive effluent turbidity
3. Time limitations

If effluent quality was satisfactory and the length of filter run had not exceeded 24 hours, the BIF unit was backwashed when the head loss through the filter reached 17 ft of water (7.5 psi).

If effluent quality was satisfactory and the length of filter run had not exceeded 24 hours, the ERD unit was backwashed when head loss through the filter reached 103 ft of water (45 psi).

At the beginning of the pilot filter study, if the turbidity of the finished water exceeded 1.0 TU or the turbidity of the raw water, whichever was lower, the units were backwashed regardless of head loss or length of filter run. However, as the study progressed, it was decided that a lower limit on effluent turbidity was necessary and during the last 6 weeks of the study, the units were backwashed whenever the effluent turbidity exceeded 0.20 TU.

If the effluent turbidity was satisfactory and the head loss through the units had not reached terminal limits within 24 hours, the units were backwashed due to time limitations. It was believed that any useful data which could be obtained from a particular run would be obtained within this period and that any extension of run length would not be beneficial.

SECTION V

SAMPLING AND ANALYSIS

SAMPLING

A 1 liter grab sample of raw water and treated water from each unit was collected during each 8-hour shift for analysis in the laboratory at the Lakewood Pumping Station. Color, pH, alkalinity, hardness, odor, and temperature were run on each sample and certain samples were also analyzed for aluminum and iron to determine if there was any carryover of coagulant into the treated water. Aluminum content was analyzed to determine the amount of alum which passed through the filters as a measure of treatment effectiveness. Grab samples of treated water were taken during periods when coliform counts in the raw water were high to determine the efficiency of the units in removing bacteria. When problems occurred with air binding of the filter units, samples were collected to determine the dissolved oxygen content of the water.

Backwash water samples were collected from Run 43 and all subsequent runs on MM-2, and Run 14 and all subsequent runs on MM-1. Depending upon which mode of operation was being used, i.e., sedimentation or no sedimentation, the backwash sample was collected either from above the filter bed and also the drain from the sedimentation basin, or only from above the filter bed. Most backwash samples were collected by grabbing a portion of backwash water at the beginning, the middle, and near the end of the backwash cycle. However, subsequent to Run 120, a continuous sampling technique was used to collect backwash samples from MM-2. The continuous sampling technique consisted of placing a siphon hose in the backwash water discharge and collecting a sample throughout the duration of the backwash cycle.

Grab samples for asbestiform fiber analysis were usually collected twice per week from the Lakewood Intake wetwell and also from the effluent of each of the pilot filters. The 1 liter samples occupied approximately 2/3 of the volume of the sample bottles. Most samples were collected in triplicate, with a portion going to Ontario Research Foundation (ORF), to the School of Medicine at the University of Minnesota at Duluth (UMD), and to NWQL at Duluth. Samples for ORF and UMD were collected in 1 liter plastic containers and samples for NWQL were collected in 18.9 liter (5 gal) plastic containers. The containers used to collect samples for asbestiform fiber analysis were either new or had been specially cleaned prior to use. In addition, each container was thoroughly rinsed three times with sample before sample collection.

CONVENTIONAL WATER QUALITY ANALYSES

Except for temperature, which was taken at the time of sample collection, analyses of the 1 liter samples collected during each shift were made daily. Color tests were conducted using Nessler tube color standards prepared according to the 13th Edition of Standard Methods.[1]

The pH of each sample was determined using a Beckman Model H-2 pH meter. Odor tests were subjective and results were recorded only as odor or no odor. Alkalinity, hardness, aluminum, and iron were determined using premeasured reagents obtained from Hach Chemical Corporation, Ames, Iowa. Bacteriological tests were made according to the 13th Edition of Standard Methods[1], using the membrane filter technique, and included total coliform, fecal coliform, and fecal streptococci tests. The suspended solids analyses made on the backwash samples and the dissolved oxygen tests were also conducted as set forth in the 13th Edition of Standard Methods.[1] Results of these tests are provided in Appendices A-3, A-4, and A-5.

TURBIDITY ANALYSES

Turbidity measurements were made with three different turbidimeters, a Hach Model 2100A Laboratory Turbidimeter, a Hach Model 1720 Low Range In-Line Turbidimeter, and a Monitek Model 215/130 In-Line Turbidimeter. The Hach 2100A unit was used during the entire study period, but the two in-line units were used only during the last 6 ½ weeks of the study. The two types of turbidimeters were studied in order to learn whether 15° forward scatter or 90° side scatter turbidimeters would be more effective in detecting fiber or turbidity breakthrough. No significant difference was observed.

The Hach 2100A utilizes a nephelometric principle of operation. Light is passed up through the sample and light striking any suspended matter in the sample is scattered at right angles to the light path. The scattered light is received by a photomultiplier tube which converts the light energy into an electrical signal for readout on a meter. Standardization of the instrument is accomplished with a set of permanent turbidity standards which simulated Formazin solutions.

The Hach low range turbidimeter also utilizes a nephelometric principle of operation but is a continuous flow unit requiring a sample flow rate of from ¼ to

½ gpm. Light passes through the sample and is scattered at right angles and received by two photoconductive cells which convert the light energy into an electrical signal for readout on a meter. Standardization can be performed with a standard reflectance rod equivalent to 5.0 turbidity units (TU), but during the pilot filtration study, the unit was standardized using the Hach 2100A unit.

The Monitek Model 215/130 turbidimeter utilizes a combination of forward light scattering and dual-beam ratio computation. The unit consists of two sub-systems, the Model 215 transmitter and the Model 130 converter. The transmitter measures the turbidity of the liquid flowing through it by projecting a thin ribbon of light through the flowing stream. A direct beam detector measures the intensity of the source light on the far side of the sight glass and the scattered light from particles in the flow is measured by a scattered beam detector. The scattered beam detector measures only light scattered in the 15° forward direction. Signals from the transmitter are received by the Model 130 converter for amplification and indication. Standardization of the unit was accomplished using a Formazin solution.

ASBESTIFORM FIBER ANALYSES

Asbestos is a non-mineralogical term for asbestiform mineral material which can be used commercially. Most of the world's asbestiform minerals are either chrysotile, a fibrous serpentine, or members of the amphibole group of silicate minerals. Chrysotile is a hydrous magnesium silicate.[2] Electron micrographs of chrysotile indicate that the fibrils are in the form of a hollow tube and chrysotile fibers, therefore, have an extremely large surface area. The chemical composition of chrysotile is hydrous magnesium silicate with trace quantities of iron and calcium. One of the most important properties of chrysotile is its positive surface electrical charge, compared to the negative surface electrical charge of fibrils in the amphibole group and almost all of the commonly used filter media such as sand, diatomite, and cellulose. This may account, in part, for the difficulty in the removal of chrysotile fibers as compared to amphibole fibers.

The amphibole group consists of crocidolite, anthophyllite, and tremolite. Amphibole fibers contain primarily iron, magnesium, calcium, and sodium and are solid and larger in diameter than chrysotile, but with a much smaller surface area on a per mass basis. A physical comparison of amphibole and chrysotile fibers is presented in Table 6. Several analytical techniques have been developed for analysis of asbestiform fiber content in water. In order to provide the most definitive quantitative and qualitative data on fiber removal in the pilot water treatment units, all available techniques were investigated prior to operation as to their effectiveness. An attempt was made to balance the accuracy of each method against the cost and time involved prior to making the final selection.

TABLE 6. COMPARATIVE PHYSICAL PROPERTIES OF AMPHIBOLE CHRYSOTILE FIBERS IN LAKE SUPERIOR WATER

Fiber	Diameter	
	μm	in x 10^{-6}
Amphibole	0.084-3.377	3.36-135.08
Chrysotile	0.054-0.168	1.92- 5.96

Transmission Electron Microscopy

The transmission electron microscope combined with electron diffraction has proven quite effective in the analysis of asbestiform fibers in water samples. Electron diffraction patterns from fibers of chrysotile have been measured with diameters in the range of 0.02 μm to 0.025 μm and lengths in the range of 0.10 μm to 0.15 μm. With electron diffraction, a specific identification of the minerals present can be made using wavelength dispersive X-ray spectrometers. Two general methods of specimen preparation technique are utilized but in both cases the fibers are specifically identified by electron diffraction patterns as they are being counted. Results from this technique are reported in number of fibers per volume of sample analyzed for both fiber groups.

The Ontario Research Foundation (ORF) in Sheridan Park, Mississaugu, Ontario, Canada utilized the transmission electron microscopy process and reported results as the number of f/l for both the serpentine (chrysotile) and amphibole groups. Results given as fiber counts and separated into amphibole and chrysotile counts will refer to data from ORF. This laboratory has been employed by the EPA on a contract basis for related western Lake Superior studies.

The ORF procedure involved collecting solid material from the water sample on a 0.1 μm pore size membrane filter by filtering approximately 200 ml of sample. The membrane filter was then ashed in a clean glass vial at a temperature of 70°C using a plasma microincineration technique. While no decomposition of the mineral fibers occurs, organic materials in the water and the filter itself are oxidized to carbon dioxide. The resultant residue was then redispersed ultrasonically in filtered distilled water and centrifuged onto a 1 cm diameter glass cover disc. The disc was dried and a carbon coating applied by evaporation that was scored and floated off onto water, carrying the fibers with it. Pieces of this material were then picked up on 200 mesh copper grids. A maximum of 10 grid squares were searched for asbestos fibers at a magnification of about 25,000 using a JEOL Model No. JEM 100U transmission electron microscope. The fibers were identified by electron diffraction and measured for both length and width. The fiber counts were processed by a computer program which calculated and plotted the fiber number and mass concentrations. The process was sensitive to a concentraton of 2 x 10^4 f/l in water, below which the data were reported as below detectable limits (BDL).[3]

Results of all ORF analyses are presented in Appendix E.

X-Ray Diffraction

The X-ray diffraction analysis process is also specific to the mineral type present and will provide identification by fiber group. It will not distinguish, however, between massive forms of the minerals and their fibrous counterparts. The detection limit of X-ray diffraction is generally not as slow as that of transmission electron microscopy. It does provide, however, a more rapid and inexpensive determination of amphibole mass concentration in water which compares well with average electron microscope fiber counts for the same samples.

The EPA National Water Quality Laboratory (NWQL) in Duluth utilized the X-ray diffraction technique and reported the concentration of suspended solids and amphibole mass in the water samples. Results from this technique were reported in mg/l of suspended solids and amphibole mass concentration. Results which refer to amphibole mass will refer to data from NWQL. The NWQL has had considerable experience in the analysis of water for asbestiform fibers through sampling provided for related studies involving many raw water and potable water intake sources in the western Lake Superior area. The results they reported could be readily compared with data from other sources they evaluated as well as provide a determination of the effectiveness of the various removal processes tested in the pilot plant operation. In addition, unavoidable sample storage time due to shipment delays prior to analysis could be held to a minimum to preclude any potential problems associated with long-term sample containment.

The NWQL procedure involved pressure filtering, at approximately 50 psi, of 25 to 40 liter samples through a preweighed Millipore 0.45 μm membrane filter. The filter was dried in an oven at 70° C and the total suspended solids in mg/l determined by the difference. A weighing correction factor was applied to compensate for a small filter weight loss due to leaching. The dry membrane filter with the sample was then fastened to a glass slide using a thin film of lacquer and examined with a Philips Model No. APD-3500 vertical X-ray diffractometer system. Amphibole mass analysis was generally sensitive to 0.005 mg/l, with the exact detection limit dependent upon the individual sample. When results were reported as "less than", the lower detection limit of the technique had been reached. Work by Cook[4] indicates a standard deviation of ±3 per cent for determining amphibole concentrations in typical samples with 0.1-0.3 mg/l amphibole. For samples having lower amphibole concentrations (< 0.1 mg/l) and suspended solids (>1.0 mg/l), this precision is reduced to ±25 per cent.[5]

Results of all NWQL analyses are presented in Appendix F.

Laboratory Selection

The two laboratories utilized for asbestiform fiber analyses, ORF and NWQL, were selected by EPA for use in the pilot plant study as representative of a number of qualified laboratories.[6] One additional facility, the University of Minnesota at Duluth, was utilized for fiber analysis. Data from this facility are presented in Appendix G.

SECTION VI

RESULTS

SEASONAL CONDITIONS

Raw water quality parameters such as pH, alkalinity, hardness, aluminum, and iron are affected very little by ambient conditions. Parameters which are affected by ambient and seasonal conditions include turbidity, water temperature, suspended solids, amphibole concentration, and bacteriological counts. Changes in climatologically related raw water quality parameters generally follow the climatological events by 1 to 2 days. This relationship is evidenced by the relatively high raw water turbidities of 5.6 TU and 6.3 TU which occurred on June 7, 1974 and June 10, 1974, respectively. These high turbidities were each preceded by a day on which rainfall in excess of 1 in, and wind velocities of 10 miles per hour (mph) or higher were recorded. Other related data are presented in Appendices A-3, A-4 and A-5.

Work by Cook[4,5] shows that the suspended solids concentration of the raw water may be increased following heavy rainfall or extended periods of high winds from the east or northeast. If the suspended solids increase is caused by heavy rainfall, generally no increase in amphibole concentration occurs. Rainfall does not cause an increase in amphibole concentrations because the suspended solids increase is the result of river runoff which contains very little amphibole mass. However, a suspended solids concentration increase caused by high wind usually results in a corresponding increase in amphibole concentration. Most of the amphibole mass contained in the raw water comes from a taconite tailings discharge at Silver Bay, Minnesota. The prevailing water circulation in western Lake Superior is counterclockwise, which results in the amphibole fibers contained in the tailings from Silver Bay being transported to the Lakewood Intake. Winds from the northeast and east promote this counterclockwise circulation, and during periods of sustained east-northeasterly winds, water with increased amphibole concentration is transported to the Lakewood Intake. High winds may also cause the resuspension of amphibole-rich sediment in the vicinity of the intake. Ice cover, which begins in January and remains until late February or March, prevents wind-generated resuspension of lake sediment.

According to Cook,[4,5] amphibole concentrations in raw water from the Lakewood Intake decrease during the summer until fall overturn occurs. Peak amphibole concentrations occur in spring and in late fall.

This trend is also evident in the amphibole data obtained by the X-ray diffraction technique during the pilot filtration study. Maximum raw water amphibole concentrations occurred from April 19 to July 19, 1974 and ranged from 0.07 to 0.26 mg/l, with an average concentration of 0.15 mg/l. From July 19, 1974 to the conclusion of the pilot filter study, the raw water amphibole concentration ranged from 0.02 mg/l to 0.10 mg/l, with an average concentration of 0.067 mg/l.

During the summer months, changes in raw water temperature are often wind-related. Offshore winds cause upwelling which brings colder water to the intake and easterly or northeasterly winds can push warm surface water into the Lakewood Intake area, causing higher water temperatures. This phenomenon is evidenced by the dramatic increase in raw water temperature which occurred on July 9, 1974. The water temperature increased from 40°F to 55°F during a period of sustained high winds from the east.

GRANULAR MEDIA FILTRATION

Asbestiform Fiber Removal

For purposes of comparison and evaluation, experimental filter runs conducted on the pilot units have been placed in categories that employed similar treatment configurations. The design and operational differences of the several pilot units have been described previously as have the physical modifications of the units, made to vary the treatment parameters. A summary of the results from each category of operation for the granular media filters is presented in Tables 7 and 8. The tables present results for asbestiform fiber removal summarized for each category in terms of a selected fiber removal goal. The successful goal chosen for either amphibole or chrysotile fiber removal is below detectable limits (BDL), or 40,000 fibers per liter, and for amphibole mass removal less than 0.005 mg/l. Details of each individual granular media run are provided in Appendices C-1 and C-2.

Turbidity Removal

It is difficult to made definitive statements concerning the effect of raw water turbidity on the effluent turbidity from the pilot filter units, because of the narrow range of raw water turbidities which occurred during the pilot filtration study. In the range of raw water turbidities which occurred, the effluent turbidity was affected more by type and amount of chemicals added than by the turbidity of the raw water, particularly with the granular media filters.

TABLE 7. GRANULAR MEDIA FILTRATION (MM-1) SUMMARY OF ASBESTIFORM FIBER REMOVAL BY CATEGORY

Categories			NWQL Amphibole Mass Results		ORF Amphibole Fiber Count Results		ORF Chrysotile Fiber Count Results	
			Samples Analyzed with Detection Limit ≤0.005 mg/l	Samples with filtrate ≤0.005 mg/l	Samples Analyzed	Samples with ≤0.04x10⁶ f/l	Samples Analyzed	Samples with ≤0.04x10⁶ f/l
MM-1 Dual Media	Filtration w/o Sedimentation 4 gpm/sq.ft. (Runs 1–40)	Alum & Anionic Polymer (Separan NP-10 or 847A) (Runs 1,2,20–24)	0	0	0	0	0	0
		Alum & Nonionic Polymer (N–17 or 985N) (Runs 4–19, 25–40)	3	2	7	6	7	0
	Sedimentation Tube Settlers 4gpm/sq.ft. (Runs 41–87)	Alum & Nonionic Polymer (985N) (Runs 41–44, 64–86)	12	12	13	13	13	2
		Alum & Nonionic Polymer (985N) and Coagulant Aid (Bentonite) (Run 87)	1	1	1	0	1	0
		$FeCl_3$ & Nonionic Polymer (985N) (Runs 45–63)	2	1	2	2	2	0

TABLE 8. GRANULAR MEDIA FILTRATION (MM–2) SUMMARY OF ASBESTIFORM FIBER REMOVAL BY CATEGORY

Categories			NWQL Amphibole Mass Results		ORF Amphibole Fiber Count Results		ORF Chrysotile Fiber Count Results	
			Samples Analyzed with Detection Limit ≤ 0.005 mg/l	Samples with filtrate ≤ 0.005 mg/l	Samples Analyzed	Samples with $\leq 0.04\times10^6$ f/l	Samples Analyzed	Samples with $\leq 0.04\times10^6$ f/l
Dual Media (Runs 1-76)	Cloquet (Runs 75,76)	Alum & Nonionic Polymer (985N) 2 gpm/sq.ft. (Run 76)	1	1	1	1	1	0
		Alum & Nonionic Polymer(985N) 4 gpm/sq.ft. (Run 75)	0	0	0	0	0	0
	Lakewood (Runs 1–74)	Alum & Nonionic Polymer (985N) 2 gpm/sq.ft. (Runs 54–56)	2	2	2	1	2	0
		FeCl3 & Cationic Polymer (C–31) 4 gpm/sq.ft. (Runs 1–13,16)	0	0	2	2	2	1
		FeCl3 & Nonionic Polymer (N–17) 4 gpm/sq.ft. (Runs 19–23)	0	0	0	0	0	0
		Alum & Nonionic Polymer (N–17 & 985N) 4 gpm/sq.ft. (Runs 24–53)	2	2	3	3	3	0
		Alum & Nonionic Polymer (985N) 6–8 gpm/sq.ft. (Runs 57–74)	0	0	3	2	3	0

TABLE 8. (CONTINUED)

Categories				NWQL Amphibole Mass Results		ORF Amphibole Fiber Count Results		ORF Chrysotile Fiber Count Results	
				Samples Analyzed with Detection Limit ≤0.005 mg/l	Samples with filtrate ≤0.005 mg/l	Samples Analyzed	Samples with ≤0.04x10⁶ f/l	Samples Analyzed	Samples with ≤0.04x10⁶ f/l
Tri. Media (Runs 77–140)	Cloquet (Run 106)	Chem. Add. to two Flash Mixers	Alum & Nonionic Polymer 4 gpm/sq.ft. (985N) (Run 106)	1	1	1	1	1	1
	Lakewood (Runs 77–105, 107–137)	Chem. Add. to Mixing Chamber	Alum & Nonionic Polymer 4 gpm/sq.ft. (985N) (Runs 77–81, 84–92)	1	1	1	1	1	0
		Chem. Add. to two Flash Mixers	Alum & Nonionic Polymer 4 gpm/sq.ft. (985N) (Runs 93–105, 107–113,115,140[a])	5	5	5	5	5	2
			Alum & Nonionic Polymer 2 gpm/sq.ft. (985N) (Run 114)	1	1	1	1	1	0
			Alum&Anionic&Cationic Poly. (A–23&Catfloc B or C–31) 4 gpm/sq.ft. (Run 116,118,139)	2	2	2	2	2	0
			Alum & Cationic Polymer 4 gpm/sq.ft. (Catfloc B) (Run 117)	0	0	0	0	0	0
			Alum & Anionic & Nonionic Polymers (A–23 & 985N) 4 gpm/sq.ft. (Runs 119,120,138)	2	2	2	2	2	0
		In-Line Mixers	Alum & Nonionic Polymer 4 gpm/sq.ft. (985N) (Runs 121,122,123)	1	1	1	1	1	1
			Alum & Nonionic & Anionic Polymers (985N & A–23) 4 gpm/sq.ft. (Runs 124,127,128)	2	2	2	2	2	0
			Alum & Anionic & Cationic Polymers (A–23 & C–31) 4 gpm/sq.ft. (Runs 125,126)	1	1	1	1	1	1
			Alum & Nonionic Polymer 6 gpm/sq.ft. (985N) (Runs 129–133)	2	2	2	2	2	0
			Alum & Cationic Polymer 4 gpm/sq.ft. (C–31) (Runs 134–137)	1	1	1	1	1	0

[a] Sedimentation Tube Settlers (Run 140)

A plot of raw water turbidity and effluent turbidity versus time for Run 31 on MM-1 is presented on Figure 6. Although the raw water turbidity increased from 0.8 TU to 4.6 TU during the run, the effluent turbidity changed only slightly, increasing from about 0.07 TU to 0.16 TU. No changes in chemical feeds or flow rate were made at the time of the turbidity increase. A similar plot of the subsequent run on the MM-1 unit on Figure 7 indicates that although the raw water turbidity varied from 1.4 to 5.6 TU, the effluent turbidity only ranged from 0.07 to 0.27 TU and the low and high effluent turbidities did not follow the low and high raw water turbidities. The chemical dosages on this run were slightly lower than those of Run 31 and turbidity breakthrough was beginning to occur at the conclusion of Run 32.

The effect of raw water turbidity on filter run lengths of the granular filters was twofold. First was the direct effect: the higher solids loading associated with a higher turbidity resulted in a more rapid rate of head loss buildup. Second was the indirect effect: higher turbidities required higher chemical dosages to maintain satisfactory effluent turbidity and these higher chemical dosages resulted in a more rapid rate of head loss buildup. For the range of raw water turbidities experienced during the pilot filtration study, the effect of the increased chemical dosages was much greater than the effect of the increased solids loading associated with a higher turbidity.

Operational Variations

Where possible, analysis of the effects of the various treatment configurations included all of one or more of the major categories listed in Tables 7 and 8. However, in many instances, a further breakdown of a major category into subsets or series of runs within that category was necessary. In this manner, a base line of treatment could be established in which all treatment variables would be held constant except for those being compared.

Runs conducted on the MM-2 unit during the period of high turbidity were made at flow rates of 116 m^3/m^2 day (2 gpm/ft^2) and 350 m^3/m^2 day (6 gpm/ft^2) and results were similar to those obtained on the MM-1 unit. Seventy-three runs with sufficient chemical dosages had satisfactory effluent turbidities regardless of raw water turbidity (within the range of raw water turbidities experienced during the pilot filtration study), and those without sufficient chemical addition had high effluent turbidities even when the raw water turbidity was less than 1.0 TU.

Table 9 shows the number of runs made on granular filters at filter rates of 4 gpm/ft^2 or higher. All of the MM-1 runs were made at 4 gpm/ft^2 and this unit

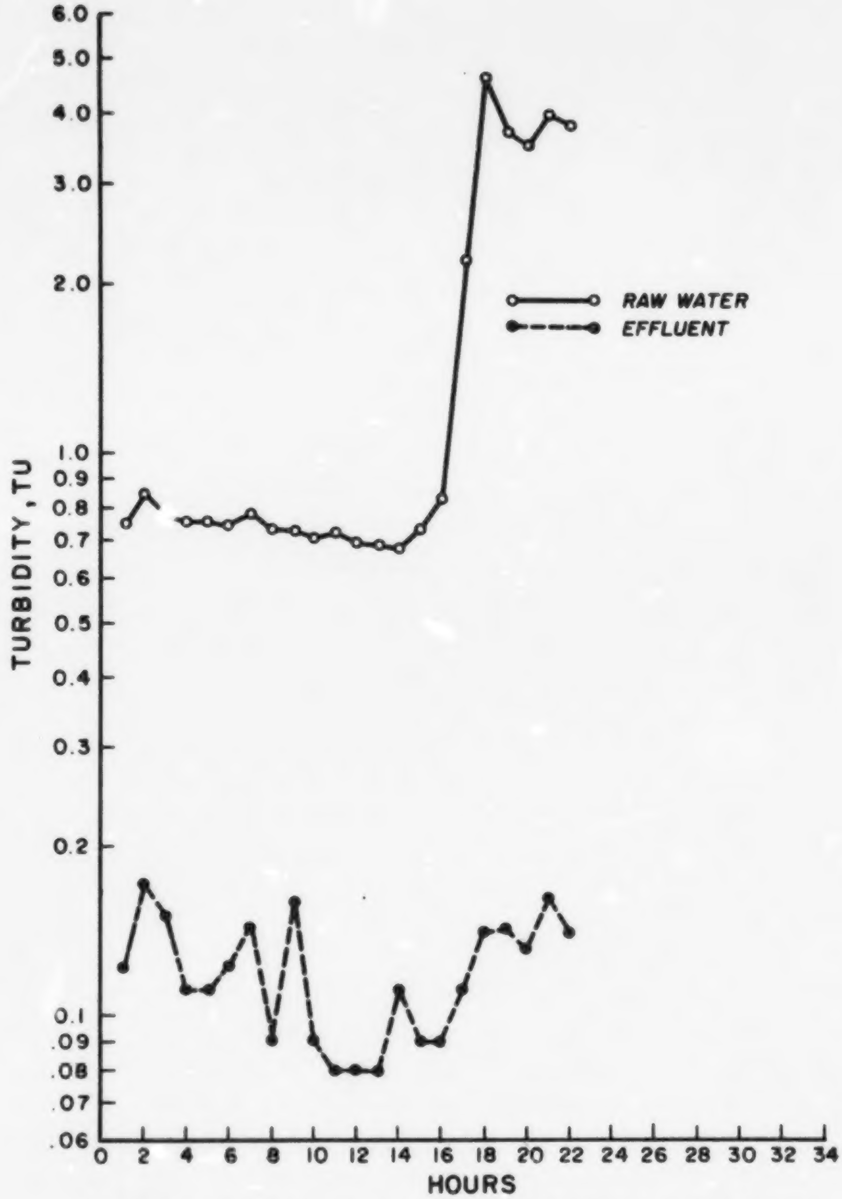

FIGURE 6. RAW WATER AND EFFLUENT TURBIDITY CURVES. UNIT MM-1 RUN 31.

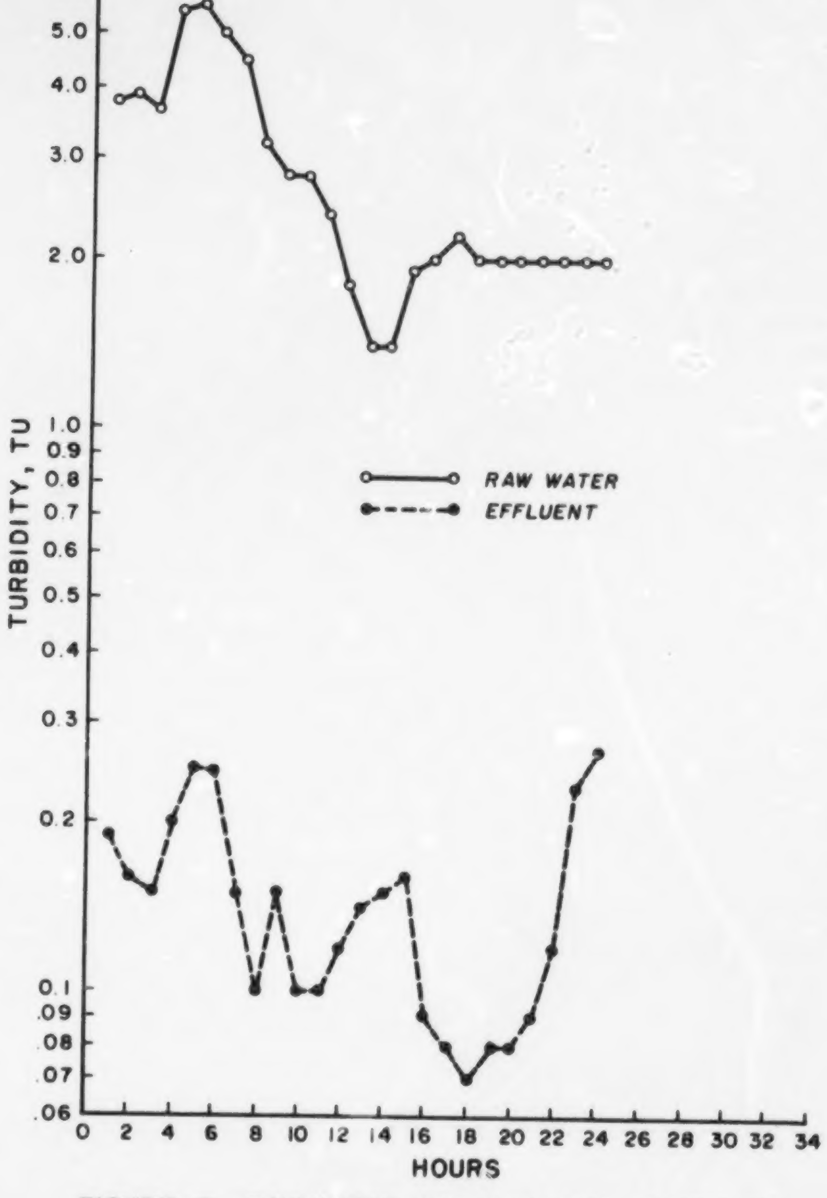

FIGURE 7. RAW WATER AND EFFLUENT TURBIDITY CURVES. UNIT MM-1 RUN 32.

was operated exclusively with dual media. Thirty-six runs at 5 gpm/ft^2 and higher rates were made on the MM-2 filter unit. Of these, 23 were made with dual media and 13 with tri-media.

TABLE 9. NUMBER OF RUNS MADE AT OR NEAR INDICATED FILTER RATES

Pilot Unit	4 gpm/ft^2	5 gpm/ft^2	6 gpm/ft^2	7 gpm/ft^2
MM-1	73	0	0	0
MM-2	85	14	8	14

Chemical Additions

Either alum or $FeCl_3$ was used as a coagulant in all of the granular media unit filter runs. A comparison of their relative effectiveness in the MM-1 unit can be made by examining the data from two major categories in which a nonionic polymer, 985N, was utilized. The data in App.C-1 show that, overall, the average raw and filtered turbidities appear to be quite similar for Runs 41-44 and 64-86 in which alum was used and Runs 45-63 in which $FeCl_3$ was used. The length of those filter runs in which alum was used was longer, however; averaging 23 hours as compared to 13 hours in those runs using $FeCl_3$.

A more direct comparison of the two coagulants may be made between Runs 41-44, utilizing alum, and Runs 45-49, utilizing $FeCl_3$. In these runs, the polymer was introduced to the floc chamber of the MM-1 unit in both cases, essentially equating the treatment processes except for the difference in coagulant. The data, from Appendix C-1, show that a slight but significant increase in turbidity removal was achieved with alum as a coagulant when the average raw and effluent turbidities of the alum runs, 0.97 TU and 0.09 TU, are compared to the average raw and effluent turbidities of the $FeCl_3$ runs, 0.68 TU and 0.13 TU. In these runs, the alum dosage averaged 16.5 mg/l and the $FeCl_3$ dosage averaged 12.1 mg/l. Filter run lengths again were longer with the alum runs, averaging 22.3 hours compared to 16.8 hours with the $FeCl_3$. Sludge solids produced and backwash volume as a per cent of the treated water were both higher in the $FeCl_3$ runs, averaging 0.051 lb/1000 gal and 2.42 per cent, as compared to 0.018 lb/1000 gal and 1.88 per cent in the alum runs.

A similar comparison can be made between alum and $FeCl_3$ in the MM-2 unit by examining Runs 24-53 in which alum was used and Runs 19-23 in which $FeCl_3$

was used. In both categories, the coagulants were used with a nonionic polymer, N-17 or 985N. As shown in App.C-2 the overall results in the two categories demonstrated a slightly better turbidity removal with alum as the coagulant by comparing average effluent turbidities of 0.20 TU with alum to 0.36 TU with $FeCl_3$. Longer filter runs were also achieved with alum as the coagulant in these categories. The data from Appendix C-2 show an average length of 14.6 hours as compared to 10.6 hours with $FeCl_3$.

Comparing directly Runs 20, 22, and 23, in which $FeCl_3$ was used, with Runs 24-27 and 34-41, in which alum was used, the data from Appendix C-2 again show that slightly better turbidity removals were achieved in the alum runs. In both sets of runs, the coagulant was introduced to the mixing chamber of the MM-2 unit and the polymer, N-17 in both series, was introduced to the first flocculation chamber of the unit. The average raw and effluent turbidities of the $FeCl_3$ runs were 0.68 TU and 0.35 TU while the average raw and effluent turbidities of the alum runs were 1.09 TU and 0.20 TU. The lengths of filter runs also were better with those runs using alum, averaging 15.1 hours as compared to 12.1 hours in the $FeCl_3$ runs. In these runs, the $FeCl_3$ dosage averaged 11.4 mg/l and the alum averaged 18.6 mg/l while the dosage of N-17 averaged approximately 0.25 mg/l in both sets of runs.

A total of four different coagulant aids or polymers were utilized in the MM-1 unit to improve the results of the use of the coagulants. The polymers were intended primarily to extend filter runs and prevent breakthrough in the filter by strengthening the chemical floc. Two anionic polymers, Separan NP-10 and 847A, and two nonionic polymers, N-17 and 985N, were used.

Mixing accomplished by the external flash mixers and the in-line mixers was more effective than the mixing provided by the pilot unit mixing system as evidenced by better turbidity removals and longer filter runs. That the external flash mixers and in-line mixers consisted of more than one stage is the probable reason for increased effectiveness. The staged systems greatly reduced the possibility of short circuiting during the mixing process and, therefore, improved the overall pilot plant operation.

As indicated in Table 10 certain filter runs with the in-line mixers produced a lower effluent turbidity than the two-stage external mixers, but at a higher cost and with a much greater possibility of turbidity breakthrough. In addition, the effluent turbidity of the runs conducted with the two-stage mixers could probably be lowered by a slight increase in alum dosage.

Dual and Tri-Media Filter Beds

The filter bed in the MM-2 unit was utilized in both a dual and a tri-media configuration to investigate the differences that the two filter beds would have on the raw water at the Duluth Lakewood Pumping Station. The results obtained using dual and tri-media filter beds are presented in Table 10. All runs selected for use in calculating the values presented in the table met the following conditions:

1. Filtration without sedimentation
2. Filter rate of 214-277 m^3/m^2 day (3.4-4.4 gpm/ft^2)
3. Filtered water temperature of 37° F to 44° F
4. Raw water turbidity of 0.46 to 0.95 TU
5. Run length is equal to time required to reach 8 ft of water head loss or 0.20 TU in effluent
6. Alum and 985N used for chemical treatment

TABLE 10. RESULTS OBTAINED USING DUAL AND TRI-MEDIA FILTER BEDS

Media	Mixing mode	No. of runs	Avg. length of runs, hr	Avg. effl. turb., TU	Avg. chem. costs $/1000 gal
Dual	Alum @ rapid mix Poly @ flocculator	5	19.4	0.12	0.0051
Tri	Alum @ rapid mix Poly @ flocculator	3	11.1	0.10	0.0044
Tri	Two-stage flash mix	7	18.9	0.10	0.0039
Tri	In-line mixers	3	20.3	0.06	0.0042

Based on data presented in Table 10, the tri-media filter bed produced lower effluent turbidities at lower chemical costs than did the dual-media filter bed. The lowest chemical cost was obtained using two-stage flash mixing prior to the tri-media filter bed and the lowest effluent turbidity was obtained using the Kenics in-line mixers prior to filtration. However, problems with turbidity breakthrough were encountered when using the in-line mixers which did not occur when using two-stage flash mixing. An increase in alum dosage probably would have lowered the effluent turbidity during those runs with two-stage flash mixing.

Filter runs conducted with Duluth raw water in the dual media bed configuration in MM-2 included three categories of filter rates. Runs 54-56 were conducted at 116 m^3/m^2 day (2 gpm/ft^2), Runs 42-5[illegible] 232 m^3/m^2 day (4 gpm/ft^2) and Runs 57-74 at 348-464 m^3/m^2 day (6-8 gpm/ft^2). For comparison purposes, those runs utilizing alum and a nonionic polymer, 985N, introduced at the same point in the treatment process were analyzed. The data in Table 8, Appendix C-1, and Appendix C-2 again show that little difference resulted in the finished water quality, with average effluent qualities of 0.14 TU, 0.18 TU, and 0.18 TU, respectively. The rate of head loss buildup did vary proportionately, however, with average filter run lengths of 41.8 hours, 18.1 hours and 10.3 hours, respectively.

Two comparisions of filtration rates can be made in the tri-media filter bed configuration in the MM-2 unit involving alum and a nonionic polymer, 985N. The first, utilizing chemical addition to the two external flash mixers as shown in Table 8 shows a slightly better turbidity removal at 116 m^3/m^2 day (2 gpm/ft^2), as compared to 232 m^3/m^2 day (4 gpm/ft^2). However, since only one run was involved at the 2 gpm/ft^2 rate, no definitive conclusions can be made.

The second comparison involves chemical addition through in-line mixers at filtration rates of 232 m^3/m^2 day (4 gpm/ft^2) and 348 m^3/m^2 day (6 gpm/ft^2). As shown in Table 8, turbidity removals were approximately the same, with average effluent turbidities of 0.06 TU and 0.10 TU, respectively. As the filter runs at 232 m^3/m^2 day (4 gpm/ft^2) were not carried to terminal conditions, no definitive comparisons of filter run lengths can be made in these two categories.

Head Loss, Filter Run Length, and Terminal Turbidity

The rate of head loss, the length of the filter run, and the terminal turbidity were factors used to evaluate the performance of the various filter configurations utilized in this study. Ideally, terminal head loss at about 8 ft of water and the beginning of turbidity breakthrough would occur at the same time with a resultant optimum filter run length.

Figure 8 shows the head loss and effluent turbidity curves of Run 107 of the MM-2 unit. These curves show that turbidity breakthrough began to occur at about the 28th hour of the filter run, a point where the head loss was about 4.5 ft of water, considerably below a terminal head loss condition.

Figure 9, the head loss and effluent turbidity curves of Run 109 of the MM-2 unit, shows terminal head loss and turbidity breakthrough occurring at about the

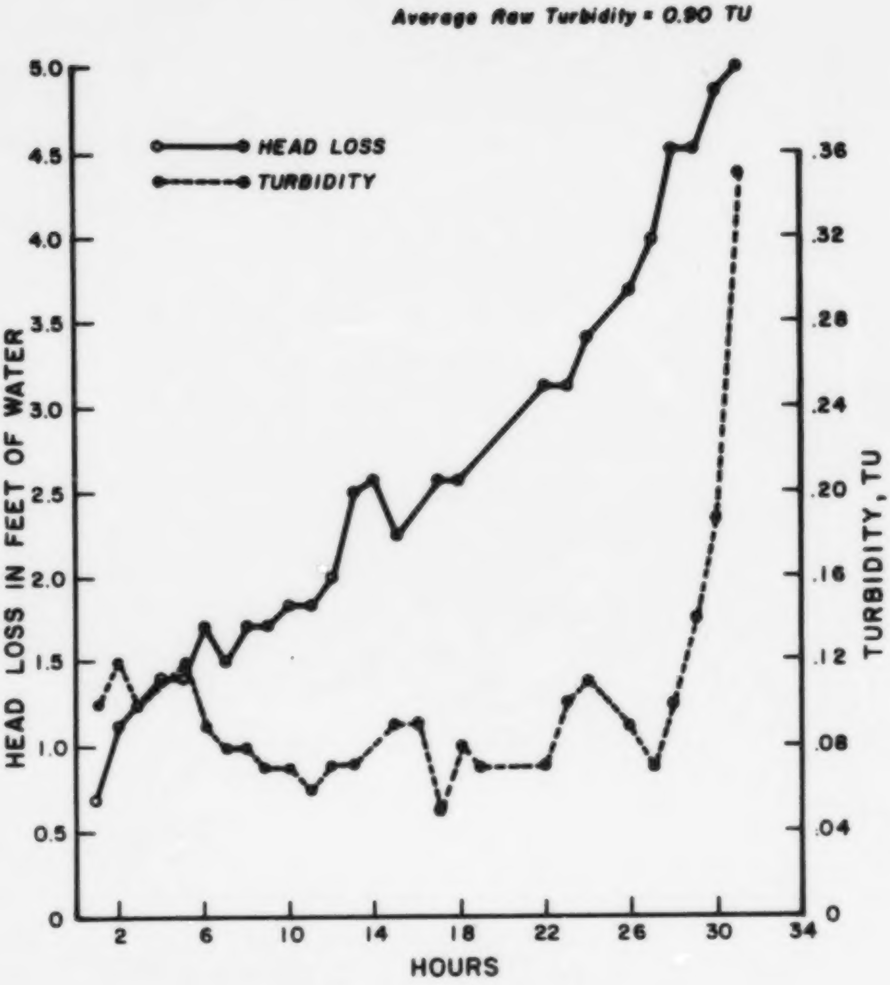

FIGURE 8. HEAD LOSS AND EFFLUENT TURBIDITY CURVES. UNIT MM-2 RUN 107.

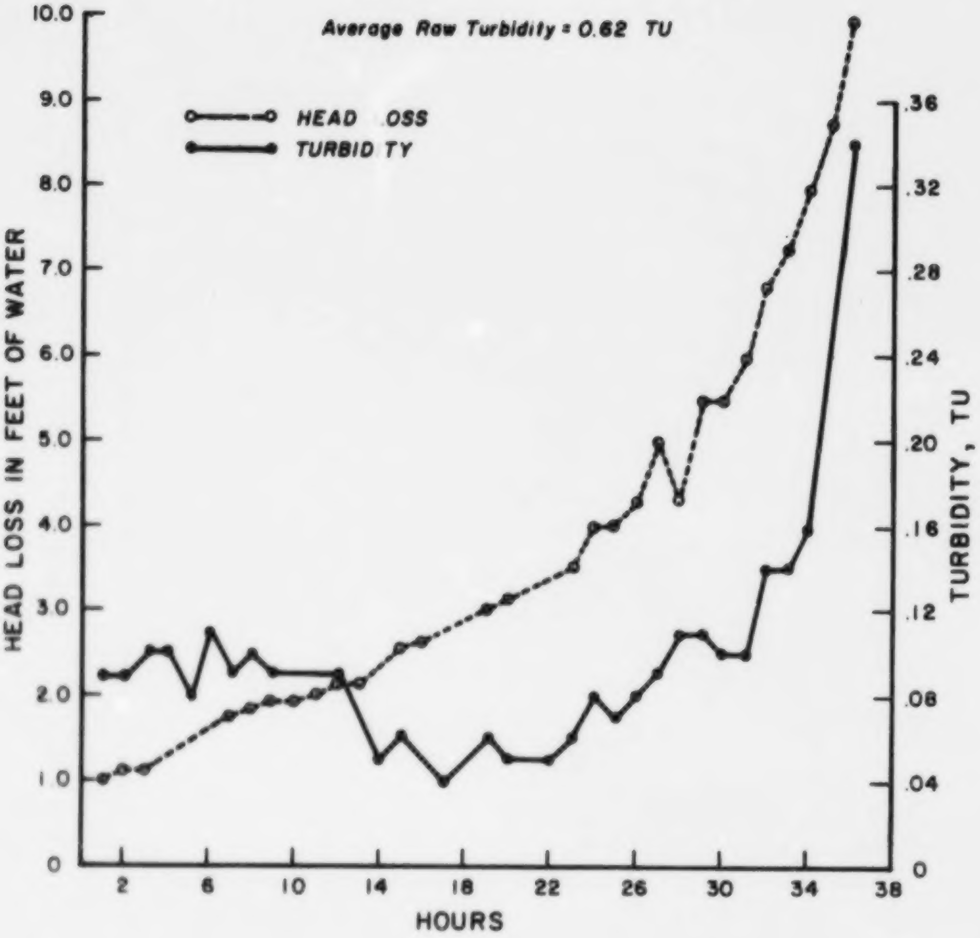

FIGURE 9 HEAD LOSS AND EFFLUENT TURBIDITY CURVES UNIT MM-2 RUN 109.

same time. This particular run was conducted for 4 hours before the run was terminated, with an average raw turbidity of 0.62 TU and an average effluent turbidity of 0.10 TU.

The terminal head loss, in feet of water, terminal turbidity, in TU, and the length of filter run, in hours, are presented in Appendices C-1 and C-2 for each filter run of the granular media units. These data reflect the progressively increasing filter run lengths that occurred with no sacrifice in effluent quality. This was due to the optimum selection of coagulants and polymers and their dosage rates that occurred as the study progressed and operating experience was gained. In addition, utilization of certain unit processes that provided better chemical mixing and flocculation, as well as better filtration, also produced a marked increase in filter run lengths as well as increased turbidity and asbestiform fiber removal. For the most part, the type and method of coagulant addition or the rate of filtration had the most effect on the rate of head loss buildup and filter run lengths. Individual head loss and turbidity curves for each granular media run are provided in Appendices D-1 and D-2.

Backwash Solids

The relationship of backwash solids to sludge volume is presented in Table 11. The values presented are based on SS tests and settleable solids tests performed on backwash water samples collected during the pilot filtration study. Sludge production given in the table is in terms of sludge produced per 1000 gallons of water treated.

TABLE 11. RELATIONSHIP OF BACKWASH SOLIDS TO SLUDGE VOLUME – UNIT MM–2

Run	Backwash solids, lb/1000 gal[a]	SS mg/l	Conc. after 60 min, %	Gal of sludge per 1000 gal
132	0.060	166	0.72	1.00
133	0.061	106	0.62	1.17
134	0.046	227	0.38	1.46
137	0.055	124	0.44	1.49
138	0.038	208	1.09	0.42
139	0.043	132	1.47	0.35

[a] Based on theoretical solids production

Backwash Water

In order to determine the asbestiform fiber concentration of the backwash water, a sample of the backwash water from the MM-2 unit, Run 138, was allowed to settle for approximately 10 days. Supernatant from the sample was withdrawn and submitted for analysis. The results indicate a low concentration of asbestiform fibers in the supernatant with 0.0152 x 10^6 f/l of amphibole and 0.57 x 10^6 f/l amphibole and 1.3 x 10^6 f/l chrysotile as reported by this same laboratory. This would indicate that supernatant from settled backwash water could be recycled for treatment after a sufficient period allowed for settling.

Filtration With and Without Sedimentation

The MM-1 unit was operated in two configurations, filtration without sedimentation in Runs 1-40 and filtration preceded by sedimentation in tube settlers in Runs 41-87. The purpose of this dual operation was to investigate the effects of sedimentation on effluent turbidity, filter breakthrough, and filter run lengths.

A comparison of the relative effects of the two configurations may be made with the results of two series of filter runs: Runs 25-40 which were conducted without sedimentation, and Runs 77-86 which were conducted with sedimentation prior to filtration. Runs 77-86 were selected for comparison as a measurement of the solids retained in the sedimentation basin which was made independently of the solids backwashed from the filter bed. In both series of runs, alum was used as the coagulant at approximately 25 mg/l and 985N as the polymer at approximately 0.05 mg/l. Turbidity removal was slightly better with sedimentation than without sedimentation. Average raw and effluent turbidities for Runs 25-40 were 1.65 TU and 0.13 TU while the average raw and effluent turbidities for Runs 77-86 were 0.79 TU and 0.09 TU.

In addition, the data from Appendix C-1 indicate that the average run lengths without sedimentation were considerably shorter than those with sedimentation, 17.8 hours as compared to 25.1 hours. An examination of the backwash solids for those runs with sedimentation revealed that the solids loading on the filter was reduced by approximately 27 per cent by the sedimentation step. It would be expected that the filter run length would be increased 37 per cent by the reduction in solids loading. In actuality, the run length increased 41 per cent.

This observation is reinforced by examining the data in Appendix C-2 for Run 115 and Run 140 on the MM-2 unit. Both of these runs were conducted with alum as the coagulant at approximately 14.5 mg/l and 985N as the polymer at approximately 0.045 mg/l. Run 115 was conducted without sedimentation and Run 140 was conducted with sedimentation prior to filtration. Again, the average raw and effluent turbidities were about the same, 0.77 TU and 0.09 TU for Run 115, and 0.47 TU and 0.06 TU for Run 140. The run length, however, was longer with Run 140 which included sedimentation, 33.6 hours as compared to 24.8 hours with Run 115. Analysis of backwash solids samples from Run 140 showed that the majority of the total solids removed were removed from the filter bed, 70 per cent, as compared to 30 per cent from the sedimentation basin.

DIATOMACEOUS EARTH FILTRATION

Asbestiform Fiber Removal

Two major types of DE media units were used in the pilot plant study. The design and operational differences of the two units have been described previously. An examination of the results of the various processes utilized is presented in this section and is summarized below.

The DE unit designated as BIF was used exclusively to provide data on vacuum filtration. One other vacuum DE unit was available, but was held in reserve. Data from vacuum DE filtration runs will be referred to as BIF data. Two DE units, designated as ERD-1 and ERD-2, were used exclusively to provide data on pressure filtration. Since the physical configuration of these two units was identical, data gathered from filter runs on these two pressure units have been combined and will be referred to as ERD data.

The data listed in Tables 12 and 13 summarize the results of the BIF and ERD runs and are used to compare sets of runs with similar treatment configurations. Details of each individual DE run are provided in Appendices C-3 and C-4.

Filter runs with the BIF unit and especially with the ERD units were quite long when conducted to their respective maximum head loss differentials. Under good quality effluent production conditions (effluent turbidity 0.2 TU or less), filter run lengths of 30 to 40 hours could be achieved easily with the BIF unit. Under similar conditions, the ERD unit could easily produce filter runs of over 60 to 70 hours duration. Once a maximum filter run length for a particular test condition had been established, filter runs were limited to a maximum of 24 hours to

TABLE 12. VACUUM DIATOMACEOUS EARTH FILTRATION SUMMARY OF ASBESTIFORM FIBER REMOVAL BY CATEGORY

			Categories	NWQL Amphibole Mass Results: Samples Analyzed with Detection Limit ≤0.005 mg/l	NWQL Amphibole Mass Results: Samples with ≤0.005 mg/l Amph. mass	ORF Amphibole Fiber Count Results: Samples Analyzed	ORF Amphibole Fiber Count Results: Samples with ≤0.04x106 f/l	ORF Chrysotile Fiber Count Results: Samples Analyzed	ORF Chrysotile Fiber Count Results: Samples with ≤0.04x106 f/l
BIF	One Step Precoat 1gpm/sqft (Runs 1T–14T 1–17)		Precoat & Body Feed only (Runs 1T–5T,6,7)	0	0	0	0	0	0
			Anionic Polymer (A-23) to Precoat (Runs 8T–14T,8)	2	1	3	2	3	1
			Nonionic Polymer (985N) to Precoat (Runs 1–5)	0	0	0	0	0	0
			Cationic Polymer (C-31 or 573C) to Precoat (Runs 9–17)	0	0	1	0	1	0
	Two Step Precoat 1gpm/sqft (Runs 18–122)	Medium Coarse DE in 1st Step of Precoat	Cationic Polymer (573C) to Total Precoat (Runs 18–24,26,29–35)	3	2	4	1	4	0
			Anionic Polymer (A–23) to Total Precoat (Runs 36–41)	6	5	1	1	0	1
			Alum to 2nd Step of Precoat (Runs 42,46,47,49–51)	1	1	2	0	2	0
			Alum & Soda Ash to 2nd Step of Precoat (Runs 60,61)	0	0	0	0	0	0
			Alum & Soda Ash to 2nd Step of Precoat and to Body Feed (Runs 62)	0	0	0	0	0	0
			Anionic Polymer (A-23) to 2nd Step of Precoat, Alum & Soda Ash to Body Feed (Runs 63-66,69–74)	3	2	3	3	3	1
		Very Coarse DE in 1st Step of Precoat	Cationic Polymer (573C) to Total Precoat (Runs 25,28)	0	0	1	0	1	0
			Alum to 2nd Step of Precoat (Runs 52–57)	0	0	0	0	0	0
			Alum & Soda Ash to 2nd Step of Precoat (Runs 58,59,89–103)	2	2	2	0	2	0
			Anionic Polymer (A–23) to 2nd Step of Precoat, Alum & Soda Ash to Body Feed (Runs 75–78, 111, 112)	2	2	2	2	2	0
			Anionic Polymer (A–23) to 2nd Step of Precoat (Runs 79, 80)	1	0	1	1	1	1
			Cationic Polymer (Catfloc B) to Raw Water (Runs 82–84, 86–88)	1	1	3	3	3	0
			Alum & Soda Ash to 2nd Step of Precoat and to Body Feed (Runs 104–109,120–122)	2	2	3	2	3	0
			Alum & Soda Ash to 2nd Step of Precoat, Cationic Polymer (Catfloc B) to Raw Water (Runs 110,113–119)	4	4	4	4	4	0

TABLE 13. PRESSURE DIATOMACEOUS EARTH FILTRATION SUMMARY OF ASBESTIFORM FIBER REMOVAL BY CATEGORY

Categories			NWQL Amphibole Mass Results		ORF Amphibole Fiber Count Results		ORF Chrysotile Fiber Count Results	
			Samples Analyzed with Detection Limit ≤0.005 mg/l	Samples with ≤0.005 mg/l Amphibole mass	Samples Analyzed	Samples with ≤0.04x10^6 f/l	Samples Analyzed	Samples with ≤0.04x10^6 f/l
ERD 1&2	One Step Precoat 1gpm/sq.ft. (Runs 1A–6A, 1–27)	Precoat & Body Feed only (Runs 2,7–11)	1	1	1	0	1	0
		Cationic Polymer to Precoat (C–31 or 573C) (Runs 1A–6A, 12–15,20)	5	5	6	3	6	1
		Alum to Precoat (Runs 21–27)	0	0	1	1	1	0
		Anionic Polymer to Precoat (A-23) (Run 3)	0	0	0	0	0	0
	Two Step Precoat 1gpm/sq.ft. (Runs 28–86)	Anionic Polymer (A-23) to 2nd Step of Precoat, Alum & Soda Ash to Body Feed (Run 72)	1	1	1	1	1	0
		Alum to 2nd Step of Precoat (Runs 28–37)	1	1	2	0	2	0
		Alum & Soda Ash to 2nd Step of Precoat (Runs 38–44, 54–60, 62–66)	6	6	6	3	6	1
		Cationic Polymer to Raw Water (Catfloc B) (Runs 45–51)	5	5	5	5	5	2
		Alum & Soda Ash to 2nd Step of Precoat and to Body Feed (Runs 67–71,82,85,86)	3	3	3	3	3	0
		Alum & Soda Ash to 2nd Step of Precoat, Cationic Polymer (Catfloc B) to Raw Water (Runs 73–76, 78–81)	3	3	3	3	3	0

permit variations of treatment within the test condition. Because of this, comparisons of filter run lengths cannot always be made and quality of effluent and asbestiform fiber removal must be relied upon for judgment criteria.

Turbidity Removal

High raw water turbidities occurred from June 6 to June 15. No other extended periods of raw water turbidities over 1.5 TU were experienced during the pilot filtration study and fluctuations in raw water turbidities in the range of 0.8 to 1.5 TU did not appear to affect effluent turbidities. A plot of raw water and effluent turbidities versus time for Run 47 on the ERD-2 unit is given on Figure 10. Raw water turbidities during this run varied from 0.84 to 1.3 TU and effluent turbidities varied from 0.08 to 0.18 TU. However, fluctuations in effluent turbidity did not follow the increases and decreases of the raw water turbidity.

As with the pressure DE unit, all runs conducted on the BIF unit during the period of high turbidities, which began on June 6, 1974, had very high effluent turbidities. A plot of raw water and effluent turbidities for Run 25 on the BIF unit is given on Figure 11.

A review of the data for BIF in Appendix C-3 shows that, on runs where the average raw water turbidity was greater than 1.5 TU, the lowest average effluent turbidity attained was 0.3 TU. This inability to attain low effluent turbidities would seem to be the result of high raw water turbidity.

Two head loss and effluent turbidity curves are presented on Figures 12 and 13. Figure 12 representing Run 110 of the BIF unit, demonstrates the steady, almost straightline head loss buildup and rather constant effluent turbidity characterized by vacuum DE units. Figure 13, representing Run 79 of the ERD-2 unit, demonstrates a typical head loss curve with a gradually diminishing rate of head loss buildup. This type of head loss curve is due to the cylindrical shape of the filter septa in which the filter surface increases as the filter cake increases, thus negating somewhat the head loss buildup in the filter cake.

Figures 14 and 15 are included to demonstrate the effect of the two-step precoat process on the initial effluent turbidity. On Figure 14, a single-step precoat procedure was used with a subsequently high initial effluent turbidity. Approximately 4 hours were required to attain the necessary filter permeability to produce a steady effluent turbidity. On Figure 15, however, a two step precoat application produced an almost immediate steady state level in the effluent turbidity. With

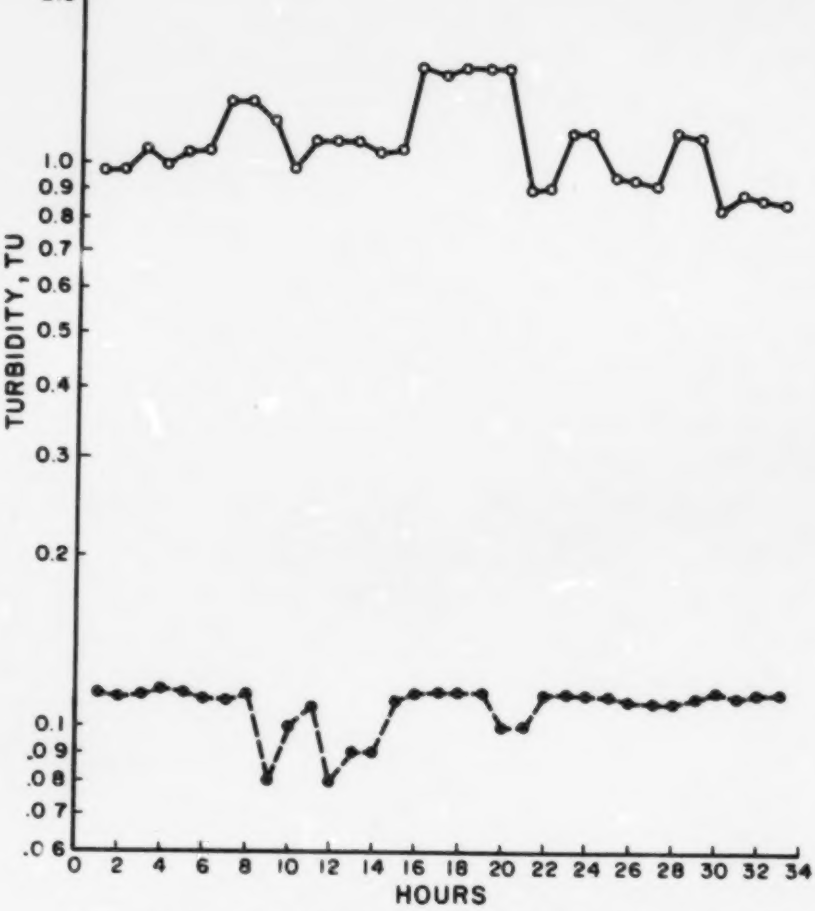

FIGURE 10. RAW WATER AND EFFLUENT TURBIDITY CURVES. UNIT ERD-2 RUN 47.

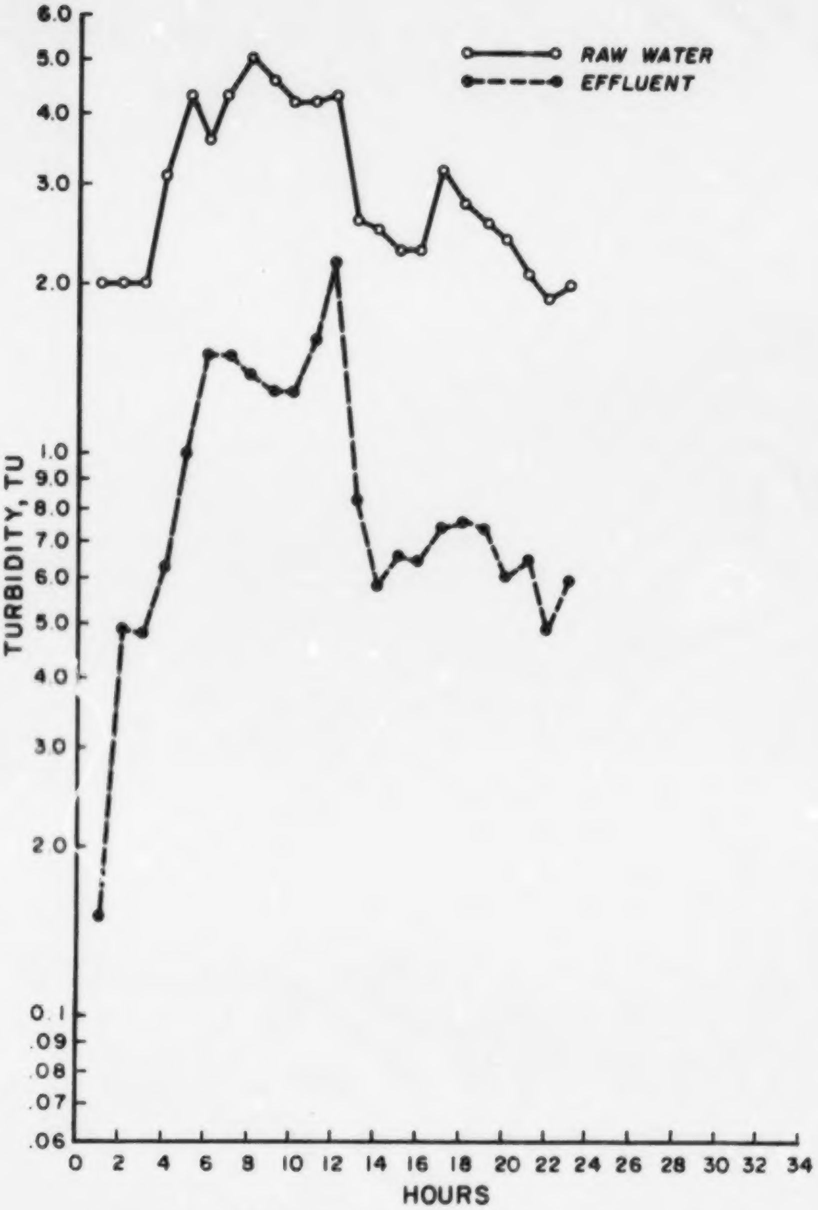

FIGURE 11 . RAW WATER AND EFFLUENT TURBIDITY CURVES. UNIT BIF RUN 25.

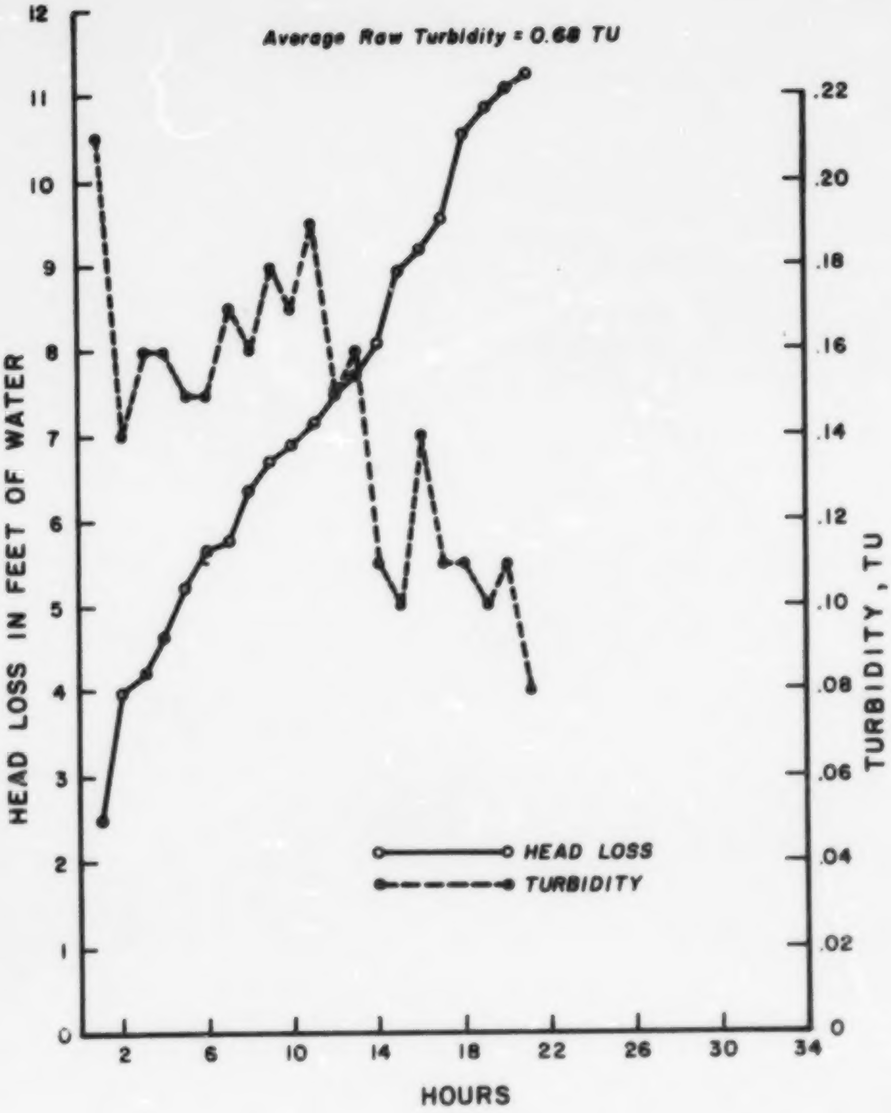

FIGURE 12 . HEAD LOSS AND EFFLUENT TURBIDITY CURVES. UNIT BIF RUN 110.

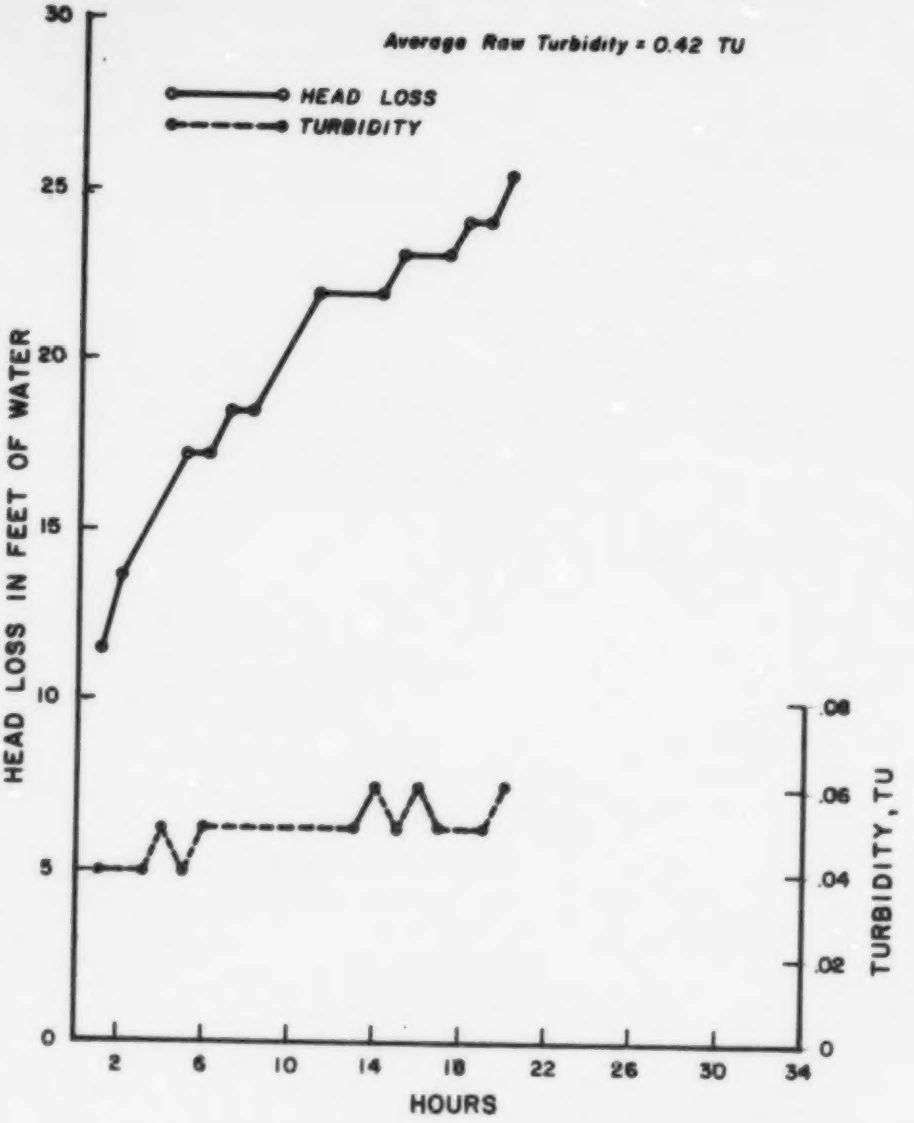

FIGURE 13 . HEAD LOSS AND EFFLUENT TURBIDITY CURVES. UNIT ERD-2 RUN 79.

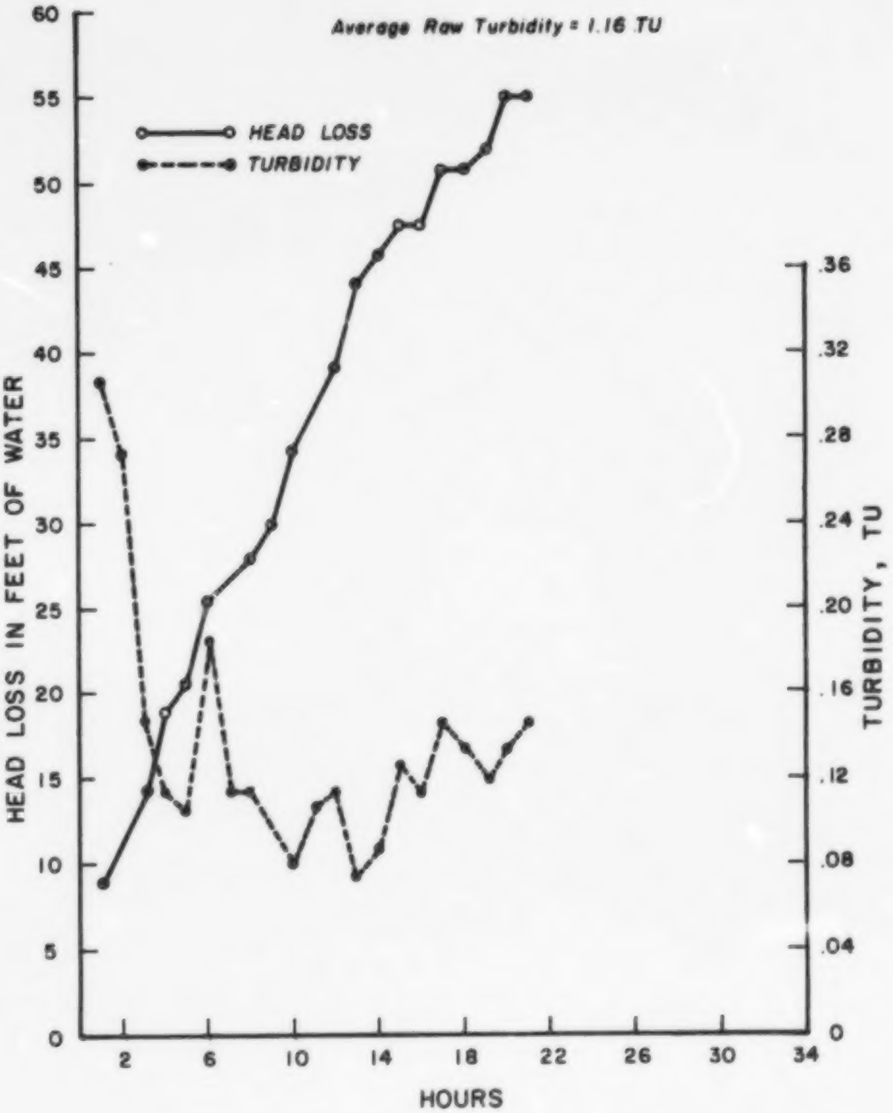

FIGURE 14 . HEAD LOSS AND EFFLUENT TURBIDITY CURVES. UNIT ERD-2 RUN 21.

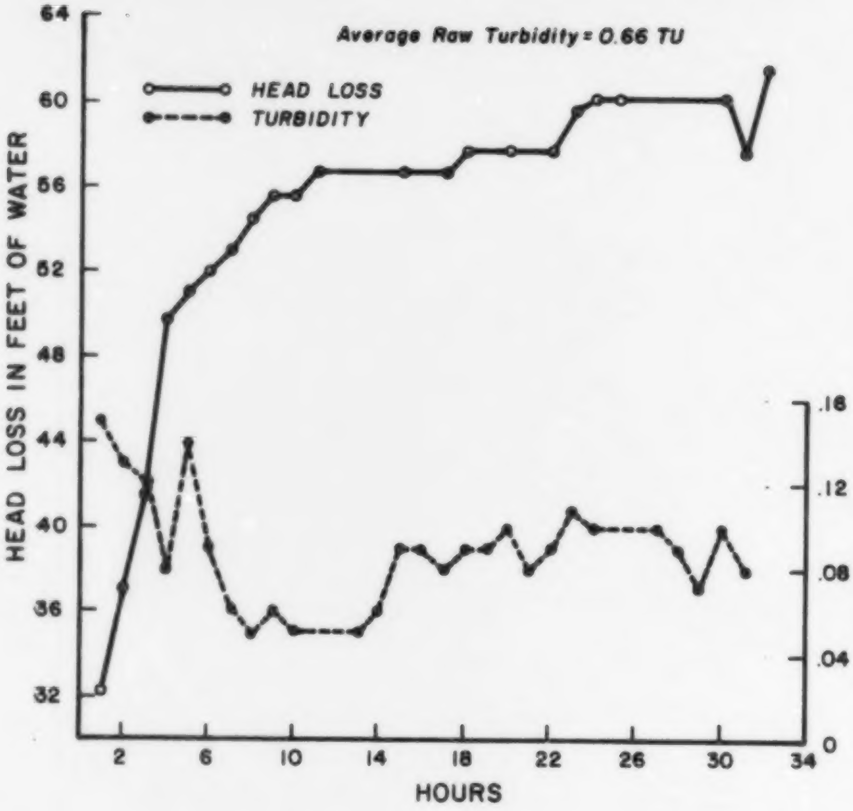

FIGURE 15. HEAD LOSS AND EFFLUENT TURBIDITY CURVES. UNIT ERD-2 RUN 34.

properly designed filter septa, two-step precoating might not be necessary for production of low initial effluent turbidities.

Operational Variations

The data listed in Tables 12 and 13 summarize the results of the BIF and ERD runs and are used to compare sets of runs with similar treatment configurations. Filter runs with the DE units were quite long when conducted to their respective maximum head loss differentials. Under good quality effluent production conditions (effluent turbidity 0.1 TU or less), filter run lengths of 30 to 40 hours with the BIF unit and 60 to 70 hours with the ERD unit could be achieved easily. Therefore, filter runs for the DE units were limited to a maximum of 24 hours to permit variations of treatment configurations.

Individual head loss and turbidity curves for each DE run are provided in Appendices D-3 and D-4.

Precoat Application

Several series of runs were conducted in both the BIF and ERD units utilizing a single level of DE for the precoat. Substantial operational and effluent turbidity problems were encountered with this procedure.

The data from Tables 12 and 13 show the relatively high effluent turbidity levels that resulted with the single precoat application. In Runs 1T-14T and 1-17 in the BIF unit, average effluent turbidity results when using a single precoat, averaged 0.47, 0.18, 0.26, and 0.35 TU. In addition, Appendix C-3 shows that several additional attempts at filter runs in the BIF unit were aborted shortly after initiation, due to initially high effluent turbidity, in all cases greater than 1.0 TU. Similar results were found when a single grade DE was used as a precoat in the ERD units. Runs 1A-6A and 1-27 produced average effluent turbidities of 0.30, 0.22, 0.10, and 0.82 TU. As with the BIF unit, several runs in the ERD single precoat series were aborted for reasons of initially high effluent turbidity, again greater than 1.0 TU, shown in Appendix C-4.

Results of the amphibole mass analysis from the NWQL listed in Tables 12 and 13 show that a significant amount of DE was passing through the filter septa in both the BIF and ERD units upon application of a single precoat of DE. This accounted, in part, for the relatively high effluent turbidity results. These conditions were particularly noticeable when the single layer of DE involved was a relatively fine grade of DE. It is probable that the openings in the filter septa used during the pilot study were not designed to retain the finer grades of DE which were required to attain the low effluent turbidities desired. For instance, Run 2T in the BIF unit and Run 2 in the ERD units utilized Hyflo Super Cel as a precoat media, a relatively fine grade of DE, with resultant average effluent turbidity levels of 0.65 and 0.56 TU, respectively.

Initially, in an attempt to prevent the DE passage through the filter septa and improve the effluent turbidity levels, two grades of DE, fine and coarse, were mixed and then coated with alum or polymer. Results from Table 12 for the BIF unit indicate that some success was achieved. Average effluent turbidity levels dropped from 0.47 TU to 0.18 TU in the case of Runs 8T-14T and Run 8 in which an anionic polymer, A-23, was added to a precoat composed of a fine and a coarse DE. Similarly, results from Table 13 for the ERD units indicate average effluent turbidity reductions from 0.30 to 0.10 TU in Runs 21-27 in which alum was added to a precoat composed of a fine and a coarse DE.

The runs conducted implementing the above two steps produced a serious operational problem involving backwashing of the filter septa. Single step precoat applications to which coagulants were added so coated the filter septa with the precoat that ordinary backwashing procedures were ineffective in removing the solution in preparation for a subsequent run.

The two-step precoat procedure was used in a series of runs with the BIF unit. In some runs, a medium coarse DE such as FW-20 or Celite 503 was used as the first precoat step while a very coarse DE such as FW-50 or Celite 545 was used in the remaining runs as the first precoat step. Polymers were added to both the first and second precoat steps in some runs. Although the average effluent turbidities were somewhat improved by the addition of polymers, the operational problem of the precoat adhering to the filter septa during backwashing still persisted. Runs in which either coagulants or polymers were added to only the second step of the precoat eliminated this operational problem. In addition, average effluent turbidity results were improved to levels as low as 0.10 and 0.08 TU in some chemical-precoat combinations.

The series of runs in the ERD units utilizing the two-step precoat procedure produced even better results. The problem of the precoat adhering to the filter media was eliminated and average effluent turbidities were reduced to levels consistently below 0.10 TU in almost all chemical-precoat combinations. In addition to the elimination of the aforementioned operational problem and the passage of DE through the filter septa, asbestiform fiber removal results became more consistent between the three reporting laboratories, especially in those runs in which optimum concentrations of chemicals were utilized.

One other variable that was considered in the precoat application process was the amount of weight of precoat per square foot of filter surface area. The initial runs conducted with the BIF unit (Runs 1T-11T) used 0.48 kg/m^2 (0.1 lb/ft^2). The precoat was increased to 0.73 kg/m^2 (0.15 lb/ft^2) in Runs 12T-14T and 1-24 in an effort to build a more cohesive precoat and prevent DE passage through the filter media. This same amount, 0.73 kg/m^2 (0.15 lb/ft^2), was also used in the ERD units in Runs 1-27. It was found, however, that during the initial phases of the runs, the effluent turbidity was quite high and required as long as 1 hour to be reduced to a consistent and acceptable level. The amount of DE in the precoat was then increased to 0.968 kg/m^2 (0.20 lb/ft^2) in a successful effort to reduce the initially high effluent turbidity. The results of this practice are reflected in the data from Runs 25-100 in the BIF unit and Runs 28-86 in the ERD units. It was also found that the stability and integrity of the precoat were enhanced in that hydraulic surges during the initial stages of the filter run would not cause the precoat to rupture. The amount of precoat used with the BIF unit was increased to 0.25 lb/ft^2 in Runs 101-122.

Body Feed

Body feed application in the BIF unit was generally divided into two major groupings. Runs 1-61 utilized three basic grades of DE in varying concentrations without the addition of any chemicals. Runs 62-122 utilized these same grades in varying concentrations, with the addition of chemicals such as alum and soda ash and a cationic polymer, Catfloc B. The three basic grades of DE utilized in Runs 1-61 included fine grades such as FW-6, Celite 512 or Speedflow, medium grades such as FW-12 or Hyflo Super Cel, or medium coarse grades such as Celite 503. The initial selection of a fine grade DE for Runs 1T-14T, 1-16 and 46-61 was made to produce a finished water with a low effluent turbidity level. However, with the discovery of the DE bleed-through problem discussed previously, and in an effort to lengthen the filter runs by reducing the rate of head loss buildup, a change was made to a coarser or medium grade DE in Runs 17-42. This change, in combination with the two step precoat process, was successful in reducing the passage of DE through the filter septa and preventing the accumulation of DE on the septa during the backwash procedure. Data from Table 12 have already been cited as showing the subsequent improved effluent turbidity levels.

The rates of body feed application in Runs 1-61 varied from approximately 40 mg/l to 340 mg/l in the case of fine media, 60 mg/l to 300 mg/l for medium grade media, and 370 mg/l for the medium coarse media. The general effect of increasing the dosage rate in all cases was to decrease the filter run length due to a faster rate of head loss buildup and increase the level of effluent turbidity removal. The increase in rate of head loss buildup with an increase in body feed rate would indicate that the body feed rates were above the optimum feed rate.

Varying the grade and dosage of body feed DE was accomplished in BIF Runs 62-122 in which chemicals were added to the body feed. A fine grade of DE was used with alum and soda ash in Runs 62-78, 107-109, and 111-112. Dosage rates varied in this series of runs from approximately 15 mg/l to 110 mg/l. The data show the general decrease in filter run lengths with an increase in dosage rate of body feed DE. For example, in Runs 107-109, body feed dosages of Celite 512 varied from 30 mg/l to 100 mg/l, respectively, while the filter run lengths decreased from 20.5 hours to 8.5 hours. This same observation was made in Runs 104-106 in which Hyflo Super Cel, a slightly coarser grade of DE, was used as the body feed. Filter run lengths varied from 22 hours with a dosage rate of 12 mg/l to 9 hours with a dosage rate of 84 mg/l.

The concentration of body feed in the ERD units varied considerably, ranging from 30 mg/l to 200 mg/l for the finer grades and 25 mg/l to 100 mg/l for the coarser grades such as Celite 545 and FW-50. It was found that the coagulants and polymers used in the precoat and body feed processes produced a greater effect on the effluent turbidity and the rate of head loss than did [illegible] grade and amount of body feed. This was probably due to the greater pressure differential produced across the filter media in the ERD units that tended to [illegible] the effects on the head loss produced by the various grades of media. In addition, contrary to the operation of the BIF unit, effective filter area of the ERD units tends to increase with increasing amounts of DE applied as body feed due to the cylindrical shapes of the septa. Consequently, the rate of head loss buildup would not be as rapid for these particular units.

Length of filter run of the DE units appeared to be affected more by changes in raw water turbidity than was the filter run length on the granular units. However, filter run length of the DE units was also affected by the amount of body feed used in proportion to the raw water suspended solids. If the body feed rate is not increased sufficiently whenever an increase in raw water suspended solids occurs, a higher rate of head loss buildup will occur, with a resultant reduction in filter run length. If the body feed is increased too much in proportion to the suspended solids, excessive thickness will be added to the filter cake, again resulting in rapid head loss buildup and a shorter filter run. Optimum body feed rates, based on the suspended solids concentration of the raw water, were not used during the pilot filtration study.

Chemical Additions

Two series of runs were conducted utilizing an anionic polymer, A-23, introduced to the total precoat in Runs 36-41 and to the second step of the precoat in Runs 79 and 80. Comparatively better effluent turbidity levels were achieved, with averages of 0.15 and 0.22 TU. In addition, it was found that introduction of the polymers to the second step of the precoat eliminated the backwashing problems previously noted. Subsequent runs were then conducted utilizing this procedure.

Alum was used in two series of runs in which it was introduced in the second precoat step. These were Runs 42, 46, 47, and 49-51 and Runs 52-57 which produced average effluent turbidity levels of 0.27 and 0.29 TU. An additional two series of runs were conducted in which soda ash was introduced with the alum. This procedure was designed to maintain the pH of the precoat solution above 7.0 so that aluminum hydroxide would form on the DE precoat. The data from these two series, Runs 58-61 and 89-103, show average effluent turbidity levels of 0.35 and 0.23 TU.

The addition of alum and soda ash to the second precoat step and to the body feed was investigated in Runs 62, 104-109, and 120-122. It was felt that the initial positive charge resulting from the addition of alum and soda ash only in the second step of the precoat was counteracted by the addition of the DE in the body feed. Constant addition of the body feed would eventually produce a net negative charge in the filter cake. With the addition of alum and soda ash in the body feed, a filter cake with a net positive charge could be maintained. Following this procedure, average effluent turbidities of 0.15 TU were produced.

In Runs 75-78, 111, and 112, an anionic polymer, A-23, was introduced in the second precoat step and alum and soda ash were added to the body feed. In the series in which a very coarse DE was used in the first step of the precoat, extremely good turbidity results were achieved, with an average effluent turbidity of 0.10 TU.

A cationic polymer, Catfloc B, was introduced to the raw water prior to filtration in Runs 82-84 and 86-88. Effluent turbidity levels averaged 0.23 TU. In Runs 110 and 113-119, this procedure was carried a step further with the addition of alum and soda ash to the second step of the precoat. Extremely good effluent turbidity results, averaging 0.08 TU, were recorded.

A program of chemical addition similar to the one followed with the BIF unit was conducted utilizing the ERD units. A single run was conducted, with an anionic polymer, A-23, added to the second precoat step, and alum and soda ash added to body feed. Excellent results were achieved, with an average effluent turbidity of 0.05 TU.

Three series of runs were conducted using alum without polymers. In the first, Runs 28-37, alum was added only to the second step of the precoat. The data show that effluent turbidities of 0.12 TU were achieved. As in the case with the BIF unit, soda ash was added to the alum in the next series, Runs 38-44, 54-60, and 62-66, to promote the alum coating process. In this series of runs, the effluent turbidities averaged 0.10 TU. In the final series of runs in this grouping, alum and soda ash were added both to the second precoat step and to the body feed. Effluent turbidities were extremely low, averaging 0.06 TU.

Runs 45-51, 73-76, and 78-81 utilized a cationic polymer, Catfloc B, added to the raw water prior to filtration. In the first series, Runs 45-51, an effluent with an average turbidity of 0.12 TU was produced. In Runs 73-76 and 78-81, with the addition of alum and soda ash to the second precoat step, the average effluent turbidity was further reduced to 0.06 TU.

Backwash Solids

The relationship of backwash solids to sludge volume is presented in Table 14. The data given is based upon results of settleable solids tests performed on samples of backwash water from the BIF and ERD units. Sludge production shown in the table is in terms of sludge produced per 1000 gallons of water treated.

TABLE 14. RELATIONSHIP OF BACKWASH SOLIDS TO SLUDGE VOLUME DE UNITS

Pilot Unit	Run	B.W. SS, lb/1000 gal[a]	B.W. SS, mg/l	Conc. @ 60 min, %	Sludge volume, gal/1000 gal
BIF	114	2.05	89,156	36.4	0.68
BIF	121	0.90	20,112	15.5	0.70
ERD-2	85	0.93	14,504	90.6	0.122

[a] Based on theoretical solids production

COMPARISON OF TURBIDIMETERS

Parallel turbidity readings on the effluent from the MM-2 unit were made using the Hach 2100A and the Hach 1720 turbidimeters. Typical data from the 2100A and 1720 units are plotted on Figure 16 and all the data collected with the units are tabulated in Appendix H. Readings obtained with the 1720 unit correlate reasonably well with those obtained with the 2100A turbidimeter.

Parallel readings on the raw water were taken with both Monitek turbidimeters and the Hach Model 2100A turbidimeter. Readings on the Monitek units were very erratic and did not correlate to readings obtained with the Hach 2100A unit until after one of the Monitek units was disassembled, the sight glass cleaned, and the unit reassembled with an air purge connected. The air purge had been tried previously with no effect on the performance of the units, apparently because the sight glass was so dirty that the source light was being deflected as it passed through the sight glass.

After the sight glass was cleaned and raw water readings on the Hach 2100A and the Monitek appeared to correlate, parallel readings were also taken on the finished waters from the ERD unit and the MM-1 unit. Typical data from the Hach 2100A and the Monitek unit are presented on Figures 17, 18, and 19 and the data are tabulated in Appendix H.

All turbidity measurements discussed in comparisons of the various pilot filter units tested will refer to data collected with the Hach 2100A unit.

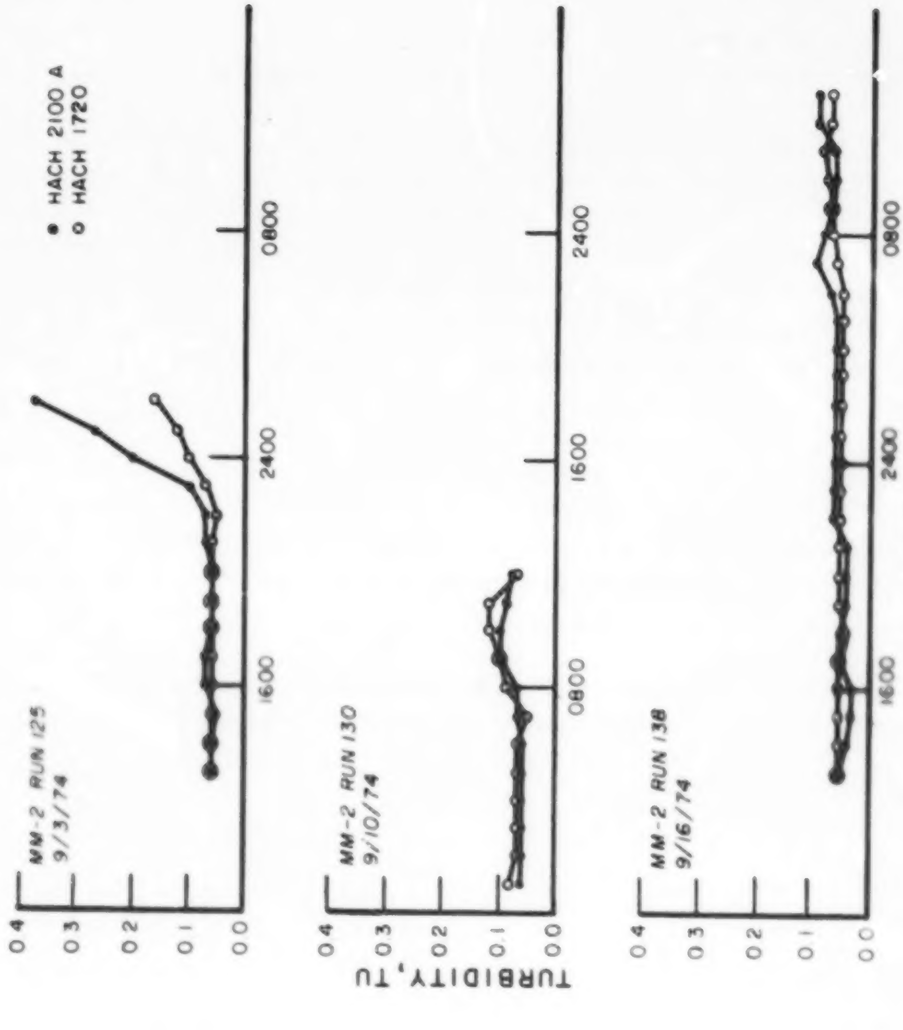

FIGURE 16 . TYPICAL MM-2 FILTERED WATER TURBIDITY READINGS OBTAINED WITH HACH 2100 A AND HACH 1720 TURBIDIMETERS.

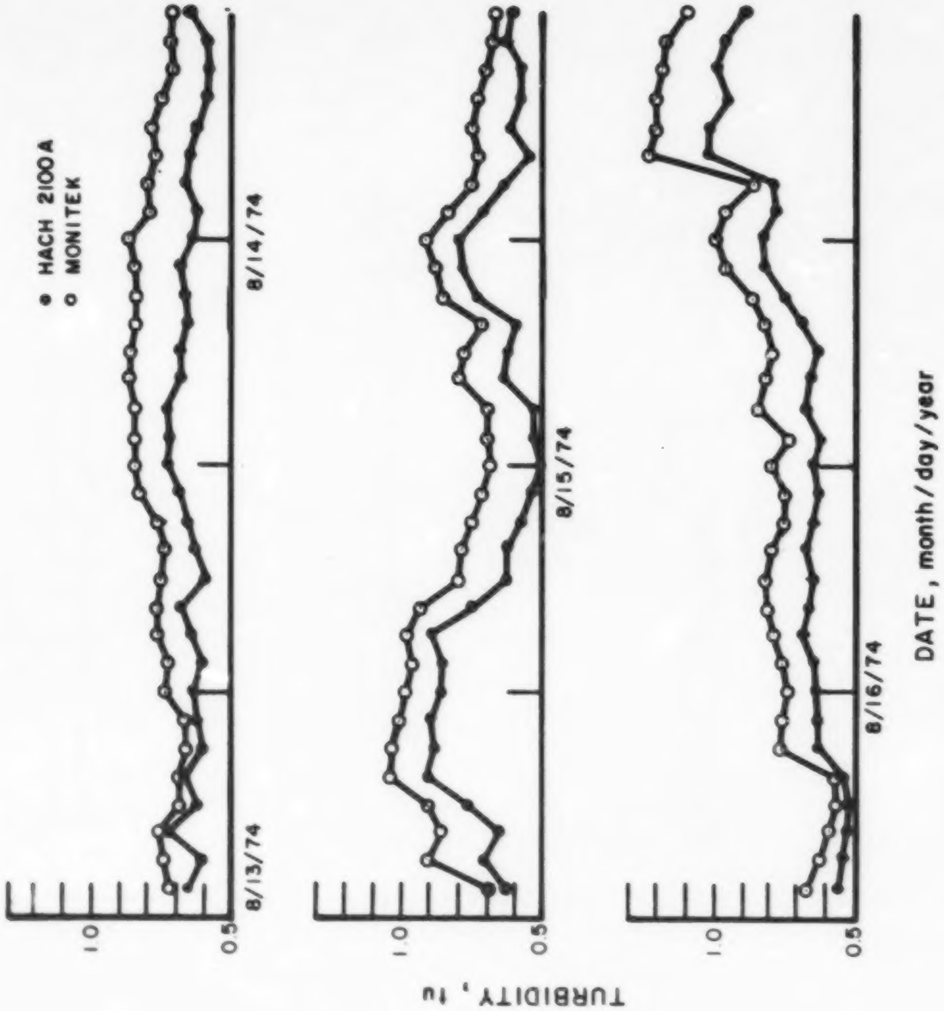

FIGURE 17. TYPICAL RAW WATER TURBIDITY READINGS OBTAINED WITH HACH 2100 A AND MONITEK TURBIDIMETERS.

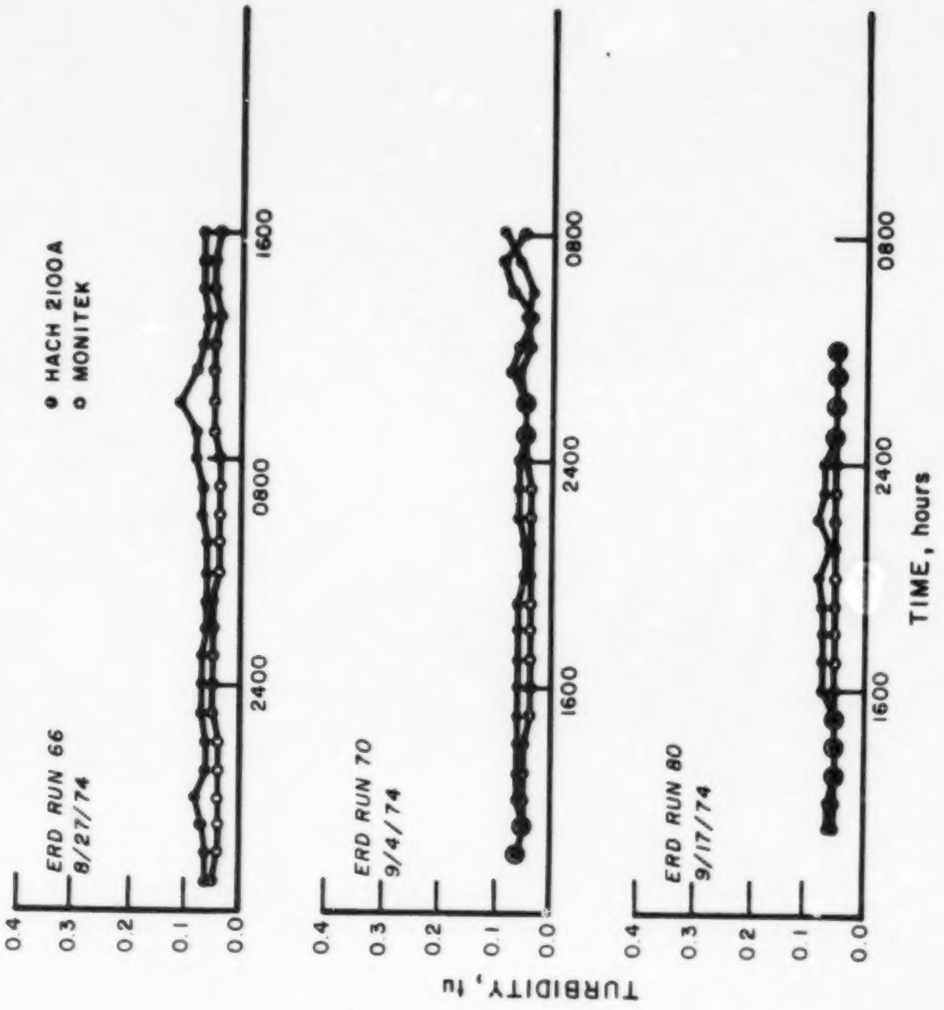

FIGURE 18 . TYPICAL ERD FILTERED WATER TURBIDITY READINGS OBTAINED WITH HACH 2100 A AND MONITEK TURBIDIMETERS.

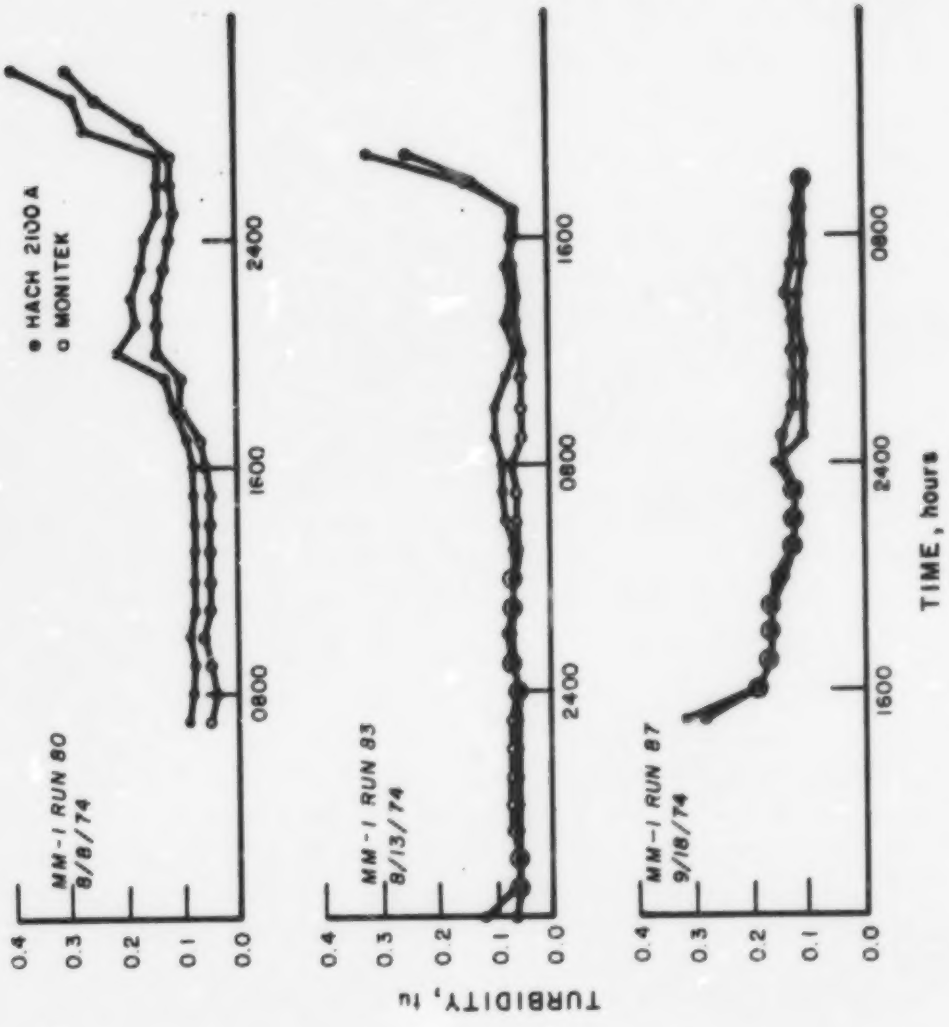

FIGURE 19. TYPICAL MM-1 FILTERED WATER TURBIDITY READINGS OBTAINED WITH HACH 2100A AND MONITEK TURBIDIMETERS.

SECTION VII

DISCUSSION

RELATIONSHIP OF TURBIDITY, ASBESTIFORM FIBER COUNT AND AMPHIBOLE MASS IN RAW WATER

Figures 20, 21, 22, and 23 present the relationships of raw water turbidity, ORF amphibole and chrysotile fiber counts, and NWQL amphibole and suspended solids concentrations, respectively. It was determined from the raw water asbestiform data that no discernible link was evident between the raw water turbidity and the asbestiform levels. Appendices E, F and G give asbestiform analytical data reported by ORF, NWQL and UMD, respectively.

GRANULAR MEDIA FILTRATION

Asbestiform Fiber Removal

In terms of fiber removal, either amphibole or chrysotile, a test run has been considered successful if BDL or a value near BDL (≤ 40,000 f/l) was reached in the filtered water.

Table 15 summarizes the ORF data on amphibole and chrysotile removal for the MM-2 runs and shows that 32 of 34 MM-2 runs for amphibole removal were successful. The two unsuccessful runs (54 and 57) were made early in the study and used dual media and single-stage mixing, which were not as effective as tri-media and two-stage mixing. Table 7 presented data on MM-1 and indicated 21 of 23 runs achieved BDL or near it for amphibole removal, but only 2 of 23 were successful for chrysotile removal. There appears to be evidence that contamination of samples may have occurred either in the process of collection or perhaps in sample preparation in the laboratory. The effects of long storage (2-7 weeks) on the detection results are not definitely known but this, too, might have had a bearing on some of the fiber counts. Hopefully, future studies will remove any uncertainties and provide more reliable chrysotile data. In spite of these points, certain evaluations on treatment effectiveness for chrysotile removal can be made and are presented in Table 16.

To achieve BDL, or close to BDL for chrysotile, it was found that the minimum alum dosage should be approximately 15 mg/l. Although MM-2 Runs 96, 105 and 122 prove to be exceptions to this by reaching BDL or near it with alum dosages less than 15 mg/l, Runs 53, 54, 55, 57, 61, 71, 99, 101, 111 and 131 (which used

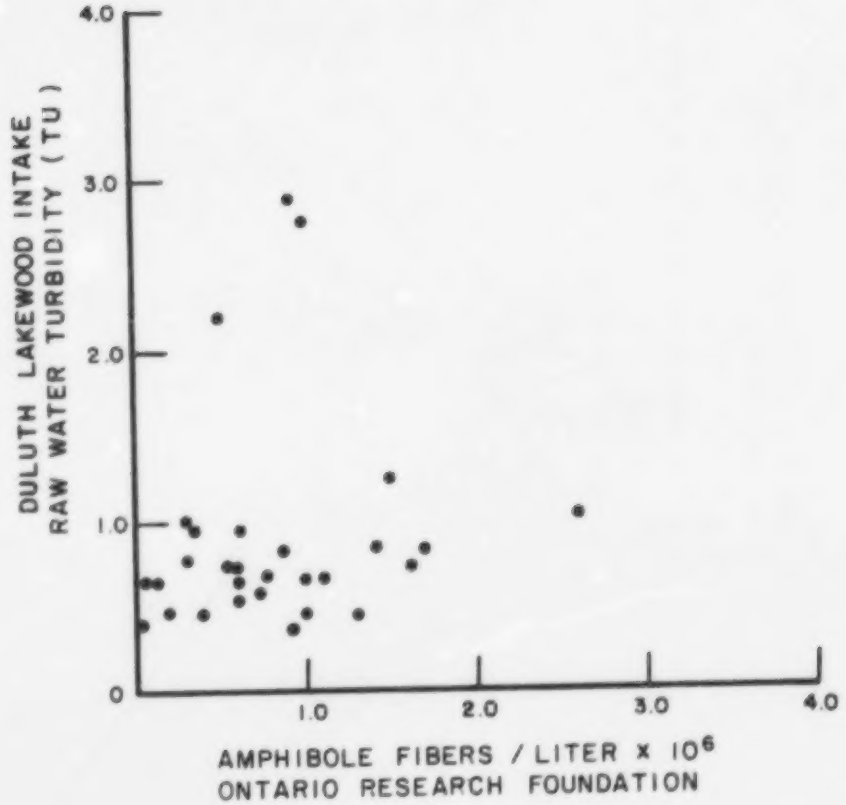

FIGURE 20. RELATIONSHIP BETWEEN RAW WATER TURBIDITY AT DULUTH LAKEWOOD INTAKE AND ORF AMPHIBOLE FIBER COUNTS.

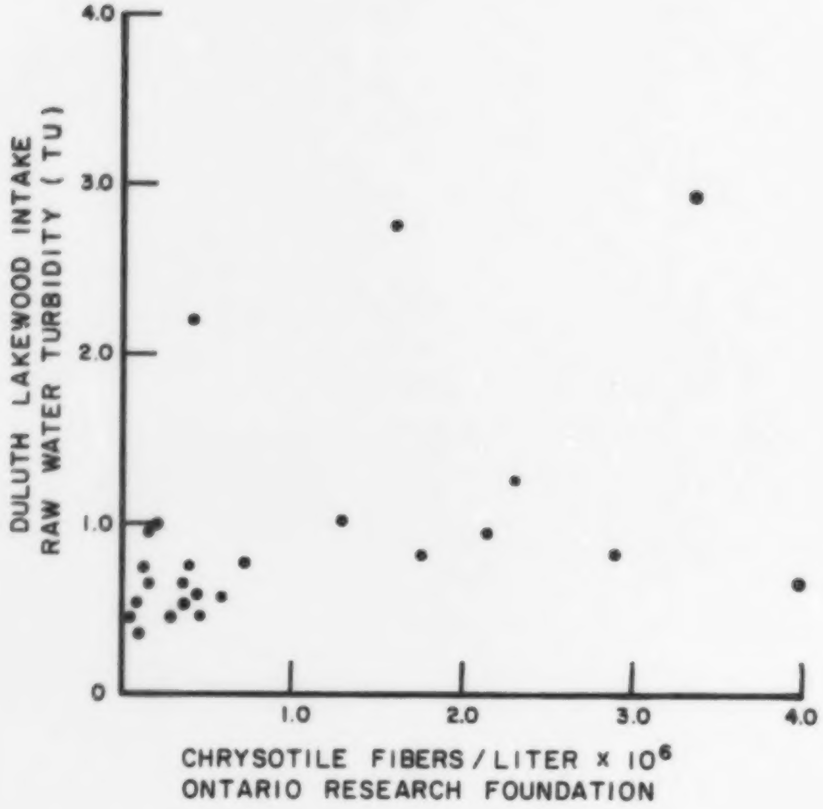

FIGURE 21 . RELATIONSHIP BETWEEN RAW WATER TURBIDITY AT DULUTH LAKEWOOD INTAKE AND ORF CHRYSOTILE FIBER COUNTS.

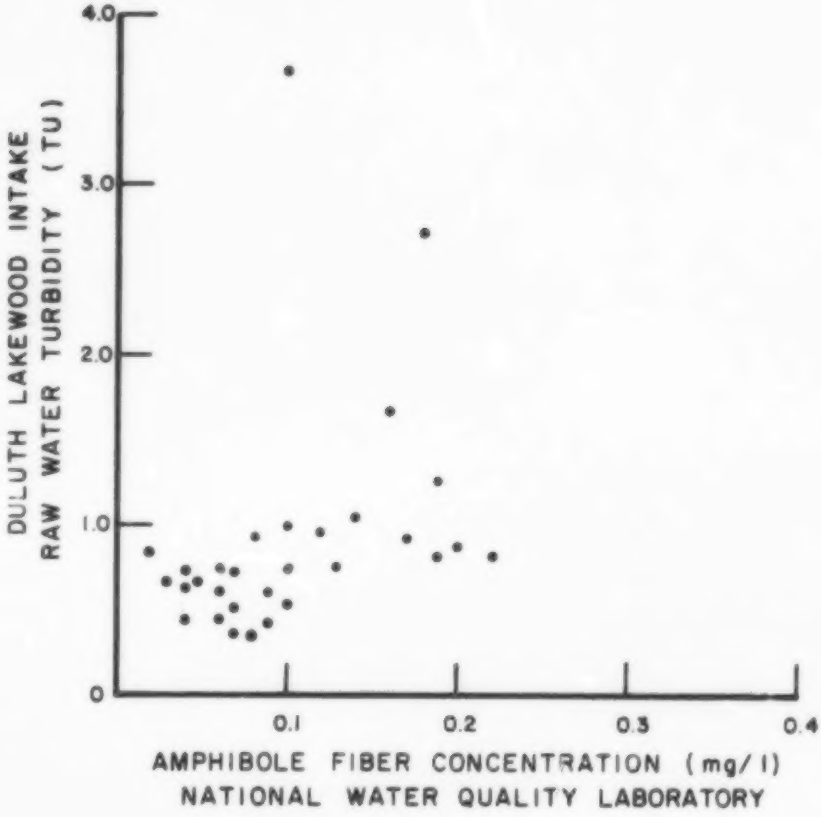

FIGURE 22. RELATIONSHIP BETWEEN RAW WATER TURBIDITY AT DULUTH LAKEWOOD INTAKE AND NWQL AMPHIBOLE MASS CONCENTRATION.

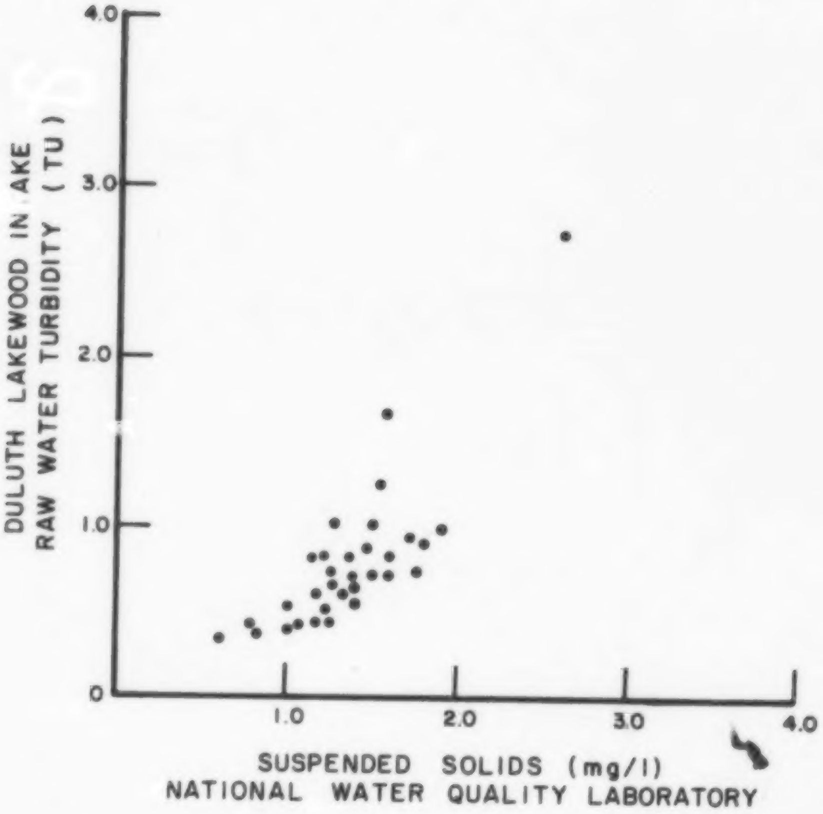

FIGURE 23. RELATIONSHIP BETWEEN RAW WATER TURBIDITY AT DULUTH LAKEWOOD INTAKE AND NWQL SUSPENDED SOLIDS CONCENTRATION.

TABLE 15. GRANULAR MEDIA FILTRATION (MM-2) AMPHIBOLE AND CHRYSOTILE REMOVAL (ORF DATA)

Run	Date	Filter Rate gpm/ft^2	Chemicals (mg/l)	Media	Stage Mixing	Amphibole Fibers x 10^6/l Raw	Amphibole Fibers x 10^6/l Filt.	Chrysotile Fibers x 10^6/l Raw	Chrysotile Fibers x 10^6/l Filt.	Filter Run Hrs.	Time to Sample Hrs.	Avg Filtered Turbidity T.U.	Remarks
1	4/19	4.95	FeCl$_3$(0.22), C-31(0.518)	Dual	1	0.304	BDL	0.217	0.04	19.6	6.5	0.4	
7	4/25	4.26	FeCl$_3$(0.61), C-31(0.626)	Dual	1	0.348	BDL	0.174	0.348	15.0	4.5	0.3	
37	5/16	3.86	Alum(18.62), N-17(0.24)	Dual	1	2.61	BDL	1.35	0.174	12.2	8.8	0.2	
50	5/30	4.01	Alum(16.0), 985-N(0.054)	Dual	1	1.42	BDL	1.83	0.913	23.7	7.5	0.1	
53	6/4	4.15	Alum(11.19), 985-N(0.053)	Dual	1	1.74	BDL	2.91	1.67	24.6	4.7	0.1	a
54	6/6	1.97	Alum(12.8), 985-N(0.052)	Dual	1	1.5	0.09	2.3	0.09	67.3	25.6	0.1	a
55	6/11	1.86	Alum(13.72), 985-N(0.050)	Dual	1	1.0	BDL	1.6	2.3	33.1	26.9	0.15	a
57	6/13	6.31	Alum(11.17), 985-N(0.051)	Dual	1	0.48	0.15	0.41	2.02	15.6	13.5	0.25	a
61	6/17	6.77	Alum(10.25), 985-N(0.037)	Dual	1	0.61	0.04	2.15	0.37	11.6	4.0	0.15	a
71	6/24	6.86	Alum (7.10), 985-N(0.079)	Dual	1	1.0	0.02	2.9	0.98	12.8	4.3	0.15	a
76	6/28	1.79	Alum(26.89), 985-N(0.159)	Dual	1	0.91	BDL	3.35	0.52	9.4	4.9	0.07	b
78	7/3	3.15	Alum(14.66), 985-N(0.079)	Tri	2	0.56	0.02	3.57	0.5	23.7	3.3	0.1	b
96	7/19	3.75	Alum(6.98), 985-N(0.060)	Tri	2	0.52	0.02	0.35	0.04	7.8	2.1	0.15	
99	7/23	4.41	Alum(8.77), 985-N(0.029)	Tri	2	0.54	BDL	0.09	0.20	17.9	7.4	0.1	a,d,f
101	7/25	4.55	Alum(9.99), 985-N(0.013)	Tri	2	0.11	BDL	1.43	0.15	19.7	13.1	0.15	a
105	7/30	4.41	Alum(10.97), 985-N(0.029)	Tri	2	0.11	BDL	0.11	0.04	25.8	4.3	0.10	
106	7/31	4.17	Alum(20.97), 985-N(0.122)	Tri	2	0.23	BDL	0.22	BDL	4.0	2.4	0.06	
107	8/1	3.20	Alum(16.19), 985-N(0.04)	Tri	2	0.22	BDL	0.15	BDL	30.8	17.9	0.08	
109	8/6	3.38	Alum(15.10), 985-N(0.043)	Tri	2	0.6	BDL	0.3	BDL	34.3	23.5	0.07	
111	8/8	4.47	Alum(11.73), 985-N(0.034)	Tri	2	0.06	BDL	0.09	0.09	25.6	9.9	0.09	a,d
113	8/13	3.88	Alum(15.30), 985-N(0.041)	Tri	2	0.13	BDL	0.2	1.4	22.6	22.3	0.06	b,d,f
114	8/15	1.97	Alum(18.93), 985-N(0.042)	Tri	2	0.09	0.02	0.17	0.22	58.6	45.7	0.06	b,f
118	8/20	4.01	Alum(15.43), C-8(0.56), A-23(0.65)	Tri	2	0.30	0.02	0.72	2.1	20.2	1.9	0.10	e,f
119	8/23	4.24	Alum(14.24), 985-N(0.042), A-23(0.28)	Tri	2	0.72	BDL	0.44	0.28	21.8	18.5	0.08	a
122	8/28	4.33	Alum(11.58), 985-N(0.049)	Tri	in-line	0.39	BDL	0.48	0.04	19.9	3.7	0.06	
124	8/30	3.92	A-23(0.160), Alum(14.93), 985-N(0.084)	Tri	in-line	0.78	0.02	0.33	0.30	19.6	3.7	0.07	
126	9/4	4.00	A-23(0.150), Alum (16.95), C-31(0.567)	Tri	in-line	1.61	BDL	0.3	BDL	17.8	9.6	0.06	
128	9/6	4.12	A-23(0.124), Alum(13.38), 985-N(0.060)	Tri	in-line	0.72	BDL	0.39	0.37	21.0	8.7	0.07	
131	9/10	6.18	Alum(13.36), 985-N(0.053)	Tri	in-line	0.6	BDL	0.5	0.5	10.0	2.8	0.07	a,c
133	9/11	5.98	Alum(24.56), 985-N(0.077)	Tri	in-line	0.3	0.02	0.3	0.3	7.4	4.3		g
137	9/13	3.98	Alum(19.66), C-31(0.790)	Tri	in-line	0.02	0.02	0.06	0.1	9.6	5.3	0.07	c,d
138	9/16	4.29	Alum(14.62), A-23(0.126), 985-N(0.065)	Tri	2	0.9	0.02	0.1	0.3	21.8	1.9	0.06	d,e
139	9/17	4.35	Alum(14.70), A-23(0.123), C-31(0.622)	Tri	2	0.2	BDL	0.1	0.1	21.4	1.5	0.07	d,e
140	9/19	3.85	Alum(14.02), 985 N(0.066)	Tri	2	0.6	BDL	0.09	0.3	31.9	1.8	0.06	b,d

[a] Alum dosage probably too low for effective chrysotile removal

[b] Chemical treatment similar to successful runs, 106, 107 & 109

[c] Turbidity breakthrough in less than 9 hours

[d] Chrysotile concentration in raw water may be too low to measure removal satisfactorily

[e] A-23 interference with alum considered possible

[f] Contamination of sample or laboratory problems suspected

[g] Great variation in final turbidity - poor run

TABLE 16. GRANULAR MEDIA FILTRATION – COMMENTS ON CHRYSOTILE REMOVAL (MM-2)

Run	Filt. Rate gpm/ft^2	Chemicals	Media	Mixing	Filtered Chrysotile (Fibers x 10^6/l)
Chrysotile Runs Which Achieved BDL					
106	4.17	Alum (20.97) 985-N (0.122)	Tri	2 Stage	BDL
107	3.20	Alum (16.19) 985-N (0.04)	Tri	2 Stage	BDL
109	3.38	Alum (15.10) 985-N (0.43)	Tri	2 Stage	BDL
126	4.00	Alum (16.95) A-23 (0.158) C-31 (0.567)	Tri	In-Line	BDL
Chrysotile Runs Which Achieved 0.04 x 10^6 fibers/l					
96	3.75	Alum (6.98) 985-N (0.060)	Tri	2 Stage	0.04
105	4.41	Alum (10.97) 985-N (0.029)	Tri	2 Stage	0.04
122	4.33	Alum (11.58) 985-N (0.049)	Tri	In-Line	0.04
Runs with Similar Treatment Which Did Not Achieve Desired Goal					
37[a]	3.86	Alum (18.62) N-17 (0.24)	Dual	Single	0.174
50[a]	4.01	Alum (16.0) 985-N (0.054)	Dual	Single	0.913
76[a]	1.79	Alum (26.89) 985-N (0.159)	Dual	Single	0.52
78[b]	3.15	Alum (14.66) 985-N (0.079)	Tri	2 Stage	0.50
113[c]	3.88	Alum (15.3) 985-N (0.041)	Tri	2 Stage	1.4
114[c]	1.97	Alum (18.9) 985-N (0.042)	Tri	2 Stage	0.22
137[c]	3.98	Alum (19.66) C-31 (0.790)	Tri	In-Line	0.1
139[c]	4.35	Alum (14.7) C-31 (0.622) A-23 (0.125)	Tri	2 Stage	0.1
140[c]	3.85	Alum (14.02) 985-N (0.066)	Tri	2 Stage	0.3
118[c]	4.01	A-23 (0.65) Alum (15.43) Catfloc B (0.56)	Tri	2 Stage	2.1
119[c]	4.24	A-23 (0.28) Alum (14.24) 985-N (0.042)	Tri	2 Stage	0.28
124[c]	3.92	A-23 (0.160) Alum (14.93) 985-N (0.064)	Tri	In-Line	0.30
138[c]	4.29	A-23 (0.126) Alum (14.62) 985-N (0.065)	Tri	2 Stage	0.3

[a] Utilized dual media and single stage flash mixing.

[b] No apparent reason for not achieving desired goal.

[c] Alum dosage too low.

low alum dosages and 985-N) support this statement in that BDL was not reached. Runs 37, 50, and 76, although utilizing alum in excess of 15 mg/l, were not successful probably due to the use of single stage flash mix and perhaps dual media. Run 78 did not achieve BDL, and there are no apparent reasons why it did not. Runs 113,114, 137, 139, and 140 failed to achieve BDL principally as a result of the effect of low chrysotile in the influent. When influent chrysotile values are low, differentation between influent and effluent values is apparently lost. Finally, Runs 118, 119, 124, 138, and 139 were not successful due to the suspected interference of A-23 and alum. This apparently was overcome in Run 126 by the presence of C-31 where an effluent chrysotile of BDL was achieved. In Run 118, Catfloc B was unable to offset the substantial dosage of A-23. Run 126 employed three in-line mixers arranged in series, with three separate chemicals fed, one upstream from each mixer.

Turbidity Removal

Table 15 shows filtered water average turbidity achieved in all MM-2 runs where asbestiform analyses were made. Raw water turbidity usually was quite low during the pilot plant study, generally less than 1.0 TU and only rarely increasing to about 4 TU. Filtered water turbidity averages in Table 15 reached a maximum of 0.4 TU for Run 1 but decreased steadily as experience led to better chemical treatment, mixing, and tri-media filtration. As shown in the table, the average final turbidities quickly dropped to less than 0.2 TU and during the last 16 runs, nearly all values were less than 0.1 TU. It is felt that granular filtration employing tri-media, together with proper chemical treatment and mixing, is capable of producing consistently a filtered water turbidity less than 0.1 TU.

Although turbidity removals were approximately the same in runs where alum was used as the coagulant, compared to runs in which $FeCl_3$ was used, filter run lengths were consistently longer in those runs where alum was used.

Design Filter Rate

Table 17 shows data on 25 additional MM-2 runs where no fiber removal analyses were made plus 6 runs with fiber analyses data. All runs were made at about 5 gpm/ft^2 or higher. This information has significance when interpreted on the basis of Figure 24 which shows the relationship between filtered water turbidity and amphibole fiber count. This figure clearly shows that when a turbidity of 0.2 TU or less was achieved, the corresponding amphibole count was 0.02×10^6 f/l in the vast majority of the samples. This fiber level was reported as BDL by ORF.

TABLE 17. GRANULAR MEDIA FILTRATION (MM-2) FILTER RATES $5\ gpm/ft^2$ AND GREATER

Run	Date	Filter Rate gpm/ft^2	Avg. Turb. Treated Water TU	Filtered Water Amphibole	Chrysotile Fibers x 10^6/l
Group 1 (No Fiber Analysis Made)					
30	5/10	5.28	0.09	–	–
51	5/31	5.09	0.43	–	–
58	6/13	5.33	0.10	–	–
59	6/14	5.65	0.13	–	–
60	6/14	6.82	0.13	–	–
62	6/18	6.84	0.19	–	–
63	6/18	6.91	0.17	–	–
64	6/19	6.86	0.18	–	–
65	6/19	6.87	0.14	–	–
66	6/20	7.82	0.12	–	–
67	6/20	6.82	0.12	–	–
68	6/20	6.89	0.15	–	–
69	6/21	7.47	0.22	–	–
70	6/21	6.78	0.30	–	–
72	6/25	6.17	0.12	–	–
73	6/25	6.64	0.15	–	–
74	6/25	6.91	0.35	–	–
85	7/10	4.85	0.12	–	–
86	7/11	4.91	0.08	–	–
87	7/11	4.94	0.14	–	–
88	7/12	4.86	0.13	–	–
89	7/12	4.79	0.08	–	–
129	9/9	6.16	0.12	–	–
130	9/10	6.09	0.07	–	–
132	9/11	5.97	0.16	–	–
Group 2 (Fiber Analysis Data Available)					
1	4/19	4.96	0.40	BDL	0.04
57	6/13	6.31	0.25	0.15	2.02
61	6/17	6.77	0.15	0.04	0.37
71	6/24	6.86	0.15	0.02	0.98
131	9/10	6.18	0.07	BDL	0.50
133	9/11	5.98	—	0.02	0.30

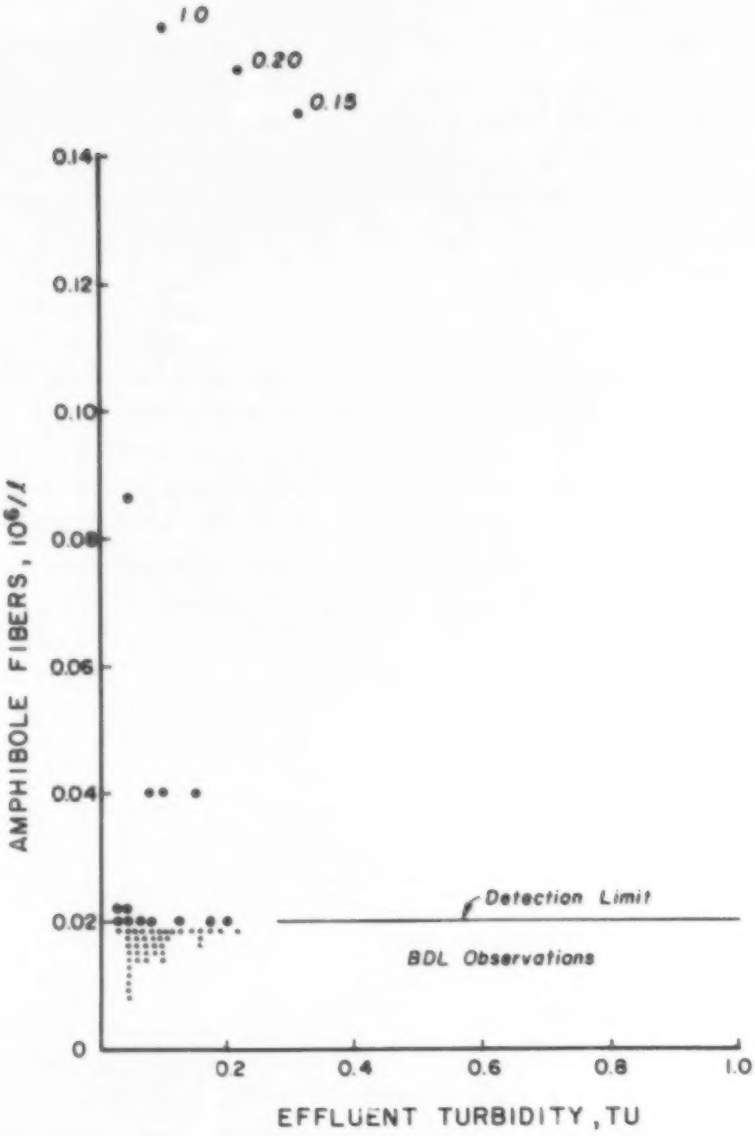

FIGURE 24 . EFFLUENT TURBIDITY VS. AMPHIBOLE FIBER COUNT GRANULAR MEDIA.

For purposes of this study, final fiber counts of 40,000 f/l or less, or BDL were considered to be successful. As shown on Figure 25, the same relationship was not apparent between effluent turbidity and chrysotile fiber count.

Table 17 shows under Group 1 that 22 of 25 runs at filter rates of 5 gpm/ft^2 or greater achieved an average turbidity of 0.2 TU or less and quite likely would have reached BDL or close to it, had asbestiform analyses been made. This data suggests that, as an initial operational guide, filter runs be terminated when turbidities reach 0.2 TU. Because some of the runs should have been terminated earlier, this would have avoided some high turbidity data and could have produced additional successful runs.

Runs 1, 61, 71, 131, and 133 shown in Table 17 under Group 2 were operated at filter rates of 5 gpm/ft^2 or greater and were successful for amphibole removal. The only other run at above 5 gpm/ft^2 (Run 57)was unsuccessful for amphibole removal and this is attributed to dual media and single-stage mixing. On this basis, 5 of 6 runs at high filter rates where fiber removal analyses were made, were successful for amphibole removal. One of the 6 runs under Group 2 was successful for chrysotile removal. Poor chrysotile removals may have been due to low alum dosage, dual media, and single stage mixing in Runs 57, 61 and 71. Low alum dosage could have been the reason in Run 131. Possible sample contamination, long storage, or laboratory problems might explain why Run 133 was unsuccessful for chrysotile removal.

Based on the above data, it is reasonable to conclude that a filter rate of 5 gpm/ft^2 with proper chemical treatment and good mixing should achieve excellent results (BDL or near it) for amphibole fiber removals.

DIATOMACEOUS EARTH FILTRATION

Asbestiform Fiber Removal

Table 18 shows fiber removal data for selected BIF (vacuum) DE runs. Three runs (8, 10T, and 12T) employing A-23 polymer in one precoat step treatment achieved success for amphibole removal in two of the runs but in only one for chrysotile removal. Four runs (37, 70, 72, and 79) used A-23 in the second precoat step and all runs were successful for amphibole removal. Two of the four runs reached BDL or near it for chrysotile removal. Runs 77 and 111 used A-23 in the second precoat step but in addition added alum and soda ash to the body feed. Both runs were successful for amphibole removal, but neither was successful for chrysotile removal. Runs 82, 84, and 88 used Catfloc B

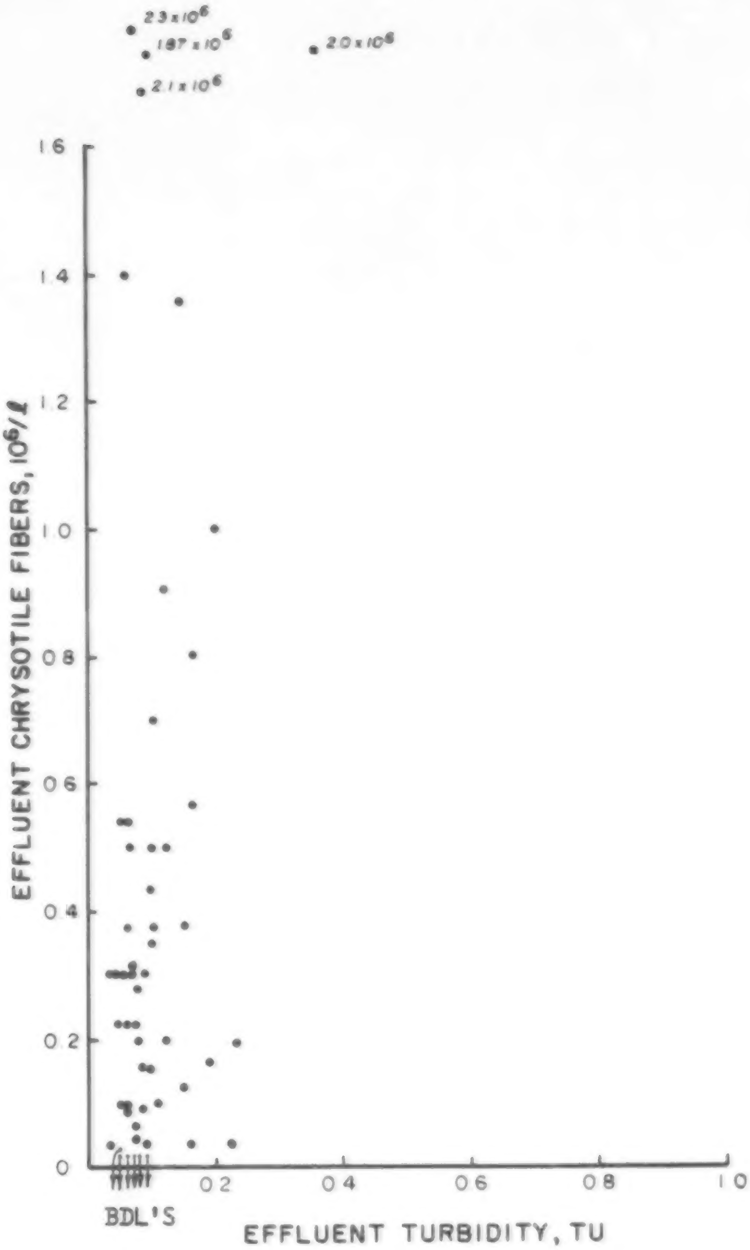

FIGURE 25. EFFLUENT TURBIDITY VS. CHRYSOTILE FIBER COUNT GRANULAR MEDIA.

TABLE 18. VACUUM (BIF) AND PRESSURE (ERD) DIATOMACEOUS EARTH FILTRATION SELECTED FILTER RUNS (ORF DATA)

Run	Date	Filter Rate gpm/ft^2	Feed To Raw Water lbs/1000 gal	First Precoat lbs/1000 gal	Second Precoat lbs/1000 gal	Body Feed lbs/1000 gal	Amphibole Fibers x 10^6/l Raw	Amphibole Fibers x 10^6/l Filter	Chrysotile Fibers x 10^6/l Raw	Chrysotile Fibers x 10^6/l Filter
Vacuum										
8	5/16	0.940	- - - -	FW-50(0.079), FW-6(0.039), A-23(0.000001.18)	- - - -	FW-6(0.560)	2.61	0.565	1.35	0.652
10T	5/7	1.035	- - - -	512(0.070), A-23(0.000002.1)	- - - -	512(0.483)	0.522	BDL	0.120	1.43
12T	5/9	0.970	- - - -	Speed flow (0.138), A-23(0.000004.1)	- - - -	512(0.611)	0.870	BDL	1.78	BDL
37	6/26	0.866	- - - -	503(0.174)	FW-6(0.174), A-23(0.000007.0)	FW-6(0.577)	1.0	BDL	3.9	0.2
79	8/1	0.877	- - - -	545(0.056)	545(0.056), A-23(0.000002.82)	512(0.577)	0.72	BDL	0.15	0.04
70	7/19	0.925	- - - -	FW-20(0.089)	512(0.089), A-23(0.000001.98)	512(0.243)	0.52	BDL	0.26	BDL
72	7/23	0.920	- - - -	503(0.063)	512(0.063), A-23(0.000001.88)	512(0.174)	0.54	BDL	0.09	0.76
77	7/30	0.958	- - - -	545(0.053)	545(0.053), A-23(0.000002.67)	512(0.213), Alum(0.012), Soda Ash(0.0061)	0.11	BDL	0.11	0.07
111	9/6	0.946	- - - -	FW-50(0.166)	512(0.111), A-23(0.000003.32)	512(0.229), Alum(0.025), Soda Ash(0.013)	0.72	0.02	0.30	0.50
62	8/6	0.818	Cat Floc B(0.014)	545(0.051)	512(0.051)	512(0.306)	0.6	BDL	0.25	0.06
64	8/8	0.826	Cat Floc B(0.0016)	545(0.114)	Super Cel(0.114)	512(0.469)	0.06	BDL	0.09	0.4
88	8/13	0.914	Cat Floc B(0.0032)	545(0.036)	512(0.036)	FW-50(0.877)	0.13	BDL	0.2	0.1
113	9/9	1.002	Cat Floc B(0.0024)	FW-50(0.100)	512(0.072), Alum(0.0080), Soda Ash(0.0040)	Super Cel(0.952)	1.0	0.04	0.5	1.0
115	9/11	0.862	Cat Floc B(0.0046)	FW-50(0.131)	512(0.088), Alum(0.0086), Soda Ash(0.0046)	512(0.460)	0.3	BDL	0.3	0.13
117	9/13	0.930	Cat Floc B(0.0035)	FW-50(0.130)	512(0.086), Alum(0.0095), Soda Ash(0.0048)	Aqua Cel(0.588)	0.02	0.02	0.06	0.4
118	9/16	0.826	Cat Floc B(0.0040)	FW-50(0.141)	512(0.094), Alum(0.010), Soda Ash(0.0052)	Aqua Cel(1.291)	0.9	BDL	0.15	1.3
Pressure										
72	9/6	1.100	- - - -	FW-50(0.067)	512(0.067), A-23(0.000002.02)	512(0.233), Alum(0.026), Soda Ash(0.013)	0.72	BDL	0.30	1.67
73	9/9	1.146	Cat Floc B(^.0047)	FW-50(0.068)	512(0.068), Alum(0.0074), Soda Ash(0.0037)	Super Cel(0.171)	1.0	BDL	0.5	1.0
78	9/13	1.093	Cat Floc B(0.0050)	FW-50(0.111)	512(0.111), Alum(0.012), Soda Ash(0.0061)	512(0.407)	0.02	BDL	0.06	0.06
79	9/16	1.093	Cat Floc B(0.0028)	FW-50(0.077)	512(0.077), Alum(0.0085), Soda Ash(0.0042)	Aqua Cel(0.228)	0.9	0.02	0.1	0.06
45	7/30	1.01	Cat Floc B(0.0040)	545(0.036)	512(0.036)	545(0.486)	0.11	BDL	0.11	0.07
46	8/1	1.087	Cat Floc B(0.0037)	545(0.054)	512(0.054)	545(0.882)	0.22	BDL	0.15	0.12
48	8/6	1.281	Cat Floc B(0.0044)	545(0.050)	512(0.050)	545(0.351)	0.6	0.02	0.3	BDL
49	8/8	1.266	Cat Floc B(0.0044)	545(0.030)	Super Cel(0.030)	FW-50(0.981)	0.06	BDL	0.09	0.04
51	8/13	1.058	Cat Floc B(0.0057)	FW-50(0.066)	Super Cel(0.066)	FW-50(0.676)	0.13	0.04	0.20	0.5

added to the raw water and all three were successful for amphibole removal but none for chrysotile. Runs 113, 115, 117, and 118 had Catfloc B added to the raw water and alum and soda ash to the second precoat step. All runs were successful for amphibole removal but none for chrysotile.

It is clear that several treatment processes in vacuum DE filtration will remove amphibole fibers successfully but the picture for chrysotile removal is far less clear. Part of the problem may be due to sample contamination, long storage, or laboratory problems. Based on the data, however, the most promising treatment for chrysotile removal of those attempted appears to require the use of A-23 in the second precoat step. This would appear to be a good starting point in any future research.

Table 18 shows fiber removal data for selected ERD (pressure) DE runs. Run 72 employed A-23 in the second precoat step and alum and soda ash in the body feed and achieved BDL for amphibole but was unsuccessful for chrysotile removal. Run 73 employed Catfloc B added to the raw water and alum and soda ash added to the second precoat step. This run resulted in BDL for amphibole but was unsuccessful for chrysotile removal, Runs 78 and 79 were performed with Catfloc B added to the raw water and alum and soda ash added to first precoat step. Amphibole removal was successfully accomplished in both runs, but neither run achieved satisfactory chrysotile removals. In Runs 45, 46, 48, 49 and 51, Catfloc B was added to the raw water. Amphibole removal was successful in all 5 runs but of chrysotile removal was successful in only 2 of the 5 runs.

It is evident that a number of treatment processes in pressure DE filtration will remove amphibole fibers but successful treatment for chrysotile removal is less apparent. Reasons for the difficulties in chrysotile removal may not all be in treatment as mentioned previously, but also in collection, transporting, and processing samples in the laboratory. Using the available data, however, the most promising treatment for chrysotile removal of those attempted appears to require addition of Catfloc B to the raw water. Addition of alum and soda ash to the second precoat step may also be worth further testing. Together with testing addition of Catfloc B to the raw water, these two processes appear to be good starting points for future studies.

Turbidity Removal

The effectiveness of DE media filters for removal of suspended material was clearly shown by the results of the pilot study. Because vacuum DE filtration caused problems due to dissolved gases, this treatment was not considered suitable for treatment of Lake Superior water. Figures 26, 27, 28, and 29 show the relationship of amphibole and chrysotile fibers vs. effluent turbidity for both vacuum and pressure DE filtration.

Appendices C-3 and C-4 provide data on pressure DE filtration. Data in these Appendices show that initial runs (1-30) produced final turbidities which generally were below 0.5 TU but sometimes approached 0.8 TU. Runs 31-60 produced lower final turbidities, generally about 0.1 TU, due to improved chemical treatment resulting from the experiences gained in the earlier runs. Beginning at Run 62 and continuing to the final Run 86, 21 runs produced final turbidities which were consistently below 0.1 TU. Of the 21 runs, 8 employed addition of Catfloc B to the raw water, and 8 others utilized alum and soda ash in the body feed. All 21 used alum and soda ash in the second precoat step. It is apparent that for the raw water turbidity range encountered during the pilot plant study it is possible to produce consistently a final water turbidity of 0.1 TU, or less, with proper chemical treatment and mixing.

SUMMARY OF COST ANALYSIS

Analysis of the results presented in Section VII indicates several categories of treatment that were essentially similar in their effectiveness for removal of asbestiform fibers and other suspended solids. These categories were examined initially in Section VII considering such parameters as success in amphibole fiber and mass removal, turbidity removal, length of filter run, rate of head loss buildup, and amount of suspended solids in backwash water. Due to the similarity of results in the various categories and in order to compare the two basic types of treatment processes, granular media filtration and diatomaceous earth filtration, an economic analysis was conducted. In this manner the cost of treating water on a per 1,000 gallon basis could be determined for each category selected and an economic comparison made among all the categories.

In the economic analysis the construction or capital costs were based on recent costs of construction for facilities with similar design and operating parameters and on costs supplied by equipment manufacturers. A treatment plant with a nominal capacity of 30 mgd was selected for a detailed analysis utilizing the same water supply as tested in the various pilot units. All cost estimates were based on December 1974 price levels. A 25 per cent contingency allowance for omissions, engineering, legal and administration costs was included in the capital costs. No factor for inflation was assumed.

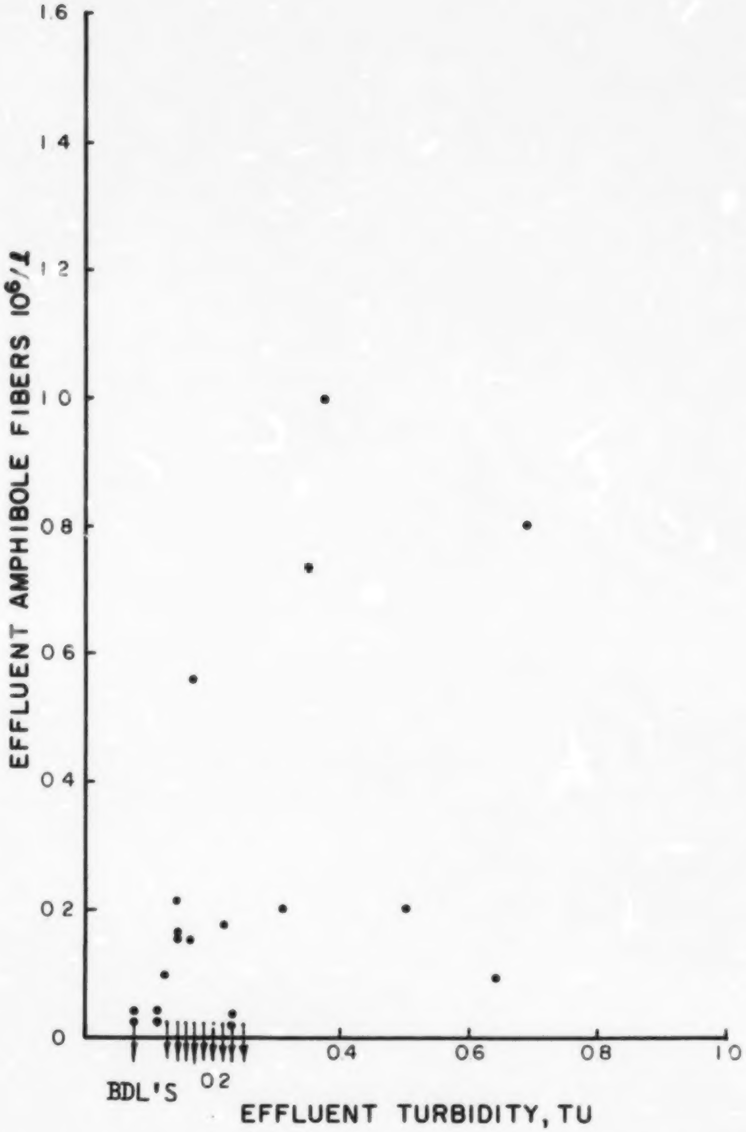

FIGURE 26. EFFLUENT TURBIDITY VS. AMPHIBOLE FIBER COUNT VACUUM DE FILTRATION.

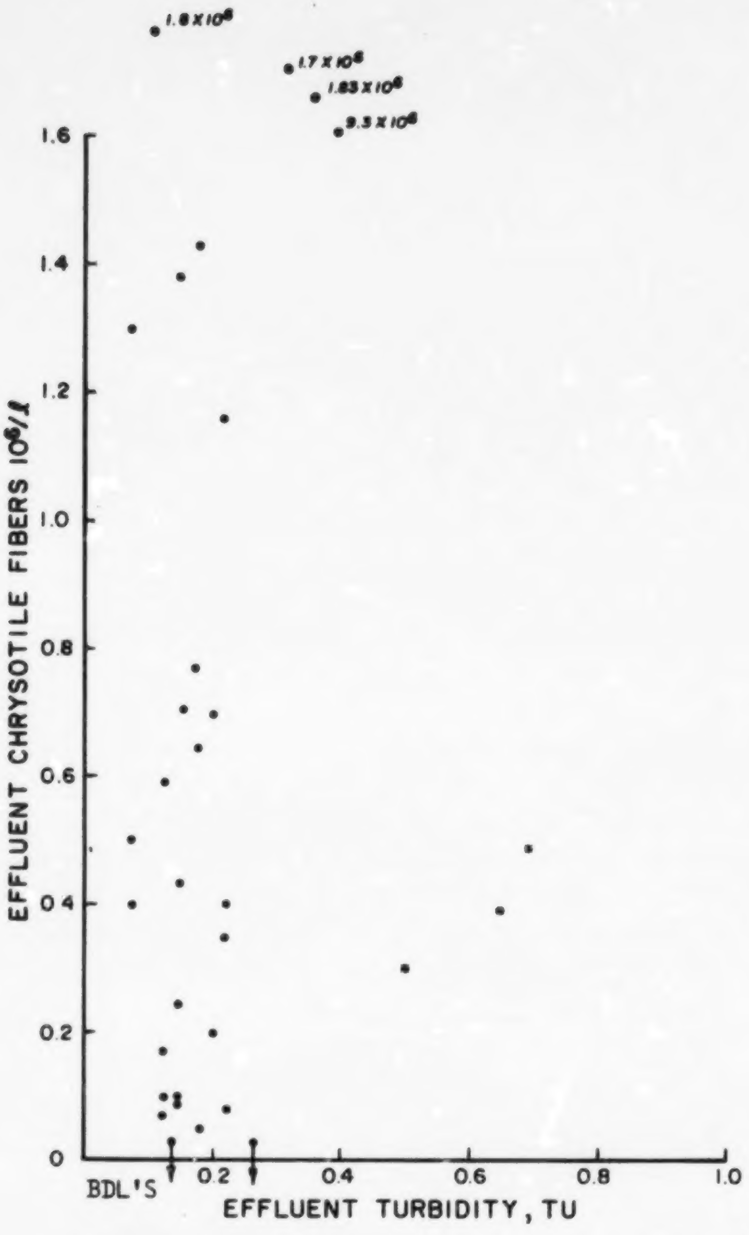

FIGURE 27. EFFLUENT TURBIDITY VS. CHRYSOTILE FIBER COUNT VACUUM DE FILTRATION.

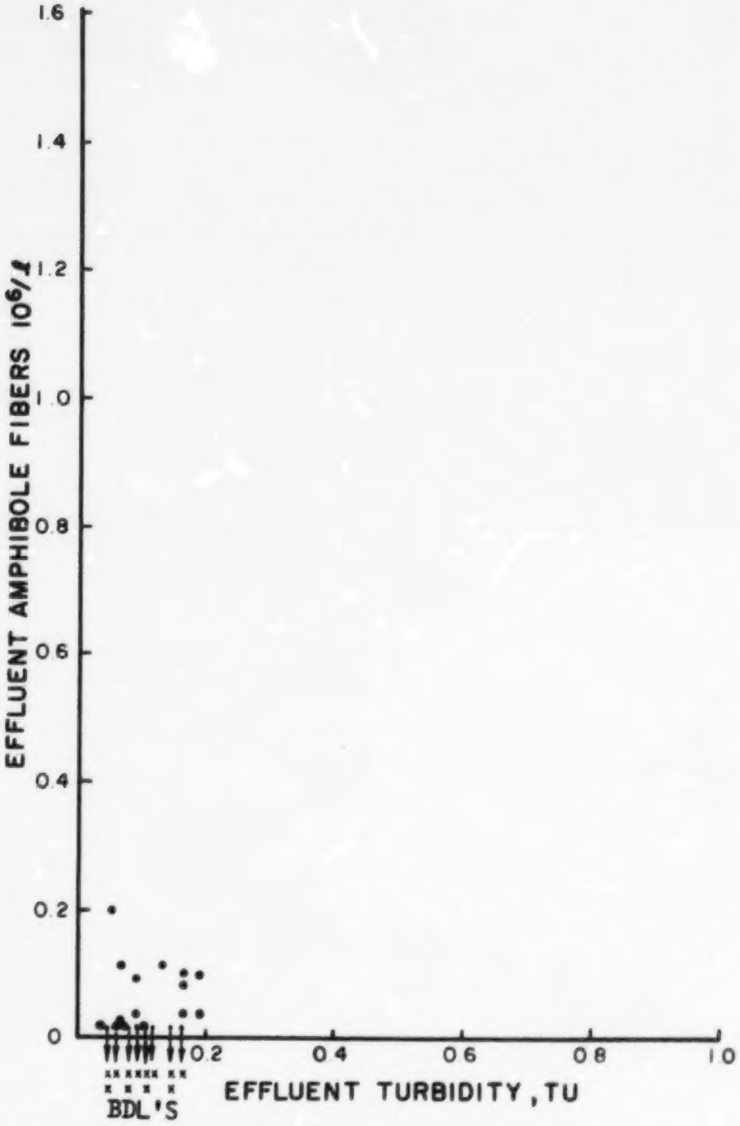

FIGURE 28. EFFLUENT TURBIDITY VS. AMPHIBOLE FIBER COUNT PRESSURE DE FILTRATION.

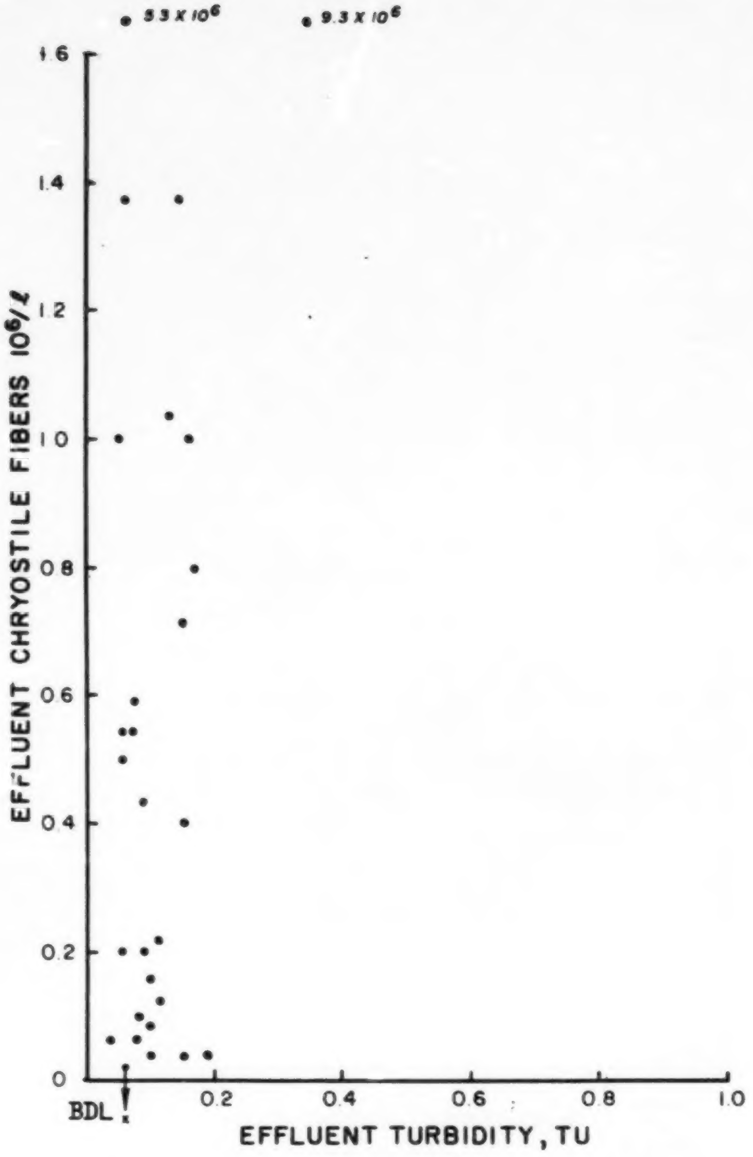

FIGURE 29 . EFFLUENT TURBIDITY VS. CHRYSOTILE FIBER COUNT PRESSURE DE FILTRATION.

Operation and maintenance cost estimates were based on those chemical costs actually incurred in the pilot plant operation and by existing water treatment plants with similar treatment processes as those considered. Solids produced in the backwash process were based on calculated amounts rather than the lower amounts found in samples analyzed during the runs, to correct for any potential sampling error. An average flow rate of 20 mgd was assumed as the basis for determining operation and maintenance costs.

A 50 year economic analysis was performed on each treatment process selected utilizing a discount rate of 5.625 per cent as required by the Federal Water Resources Council for making economic comparisons of alternative projects. Total first costs, replacement costs, average annual costs, and cost per 1,000 gallons of water treated were determined.

Granular Media Filtration

Three categories of treatment were selected from the runs utilizing granular media filtration. The selection of these categories had, as a common base, amphibole fiber count and mass removal to a level near or below the detectable limits (BDL) of the analytical equipment and an average effluent turbidity of 0.1 TU or less. Economically, the three categories were quite attractive, with average chemical costs of 0.35, 0.4, and 0.5 ¢/1000 gallons, respectively, as compared to the range of average chemical costs for all granular media runs of 0.35 to 1.26 ¢/1000 gallons.

The first category, or treatment process, selected utilized dual media filtration with single-stage mixing as represented by MM-1 Runs 28, 29, 30, 39, and 40 and MM-2 Runs 50 and 53. Alum and a nonionic polymer, 985N, were introduced at average rates of 15 and 0.05 mg/l, respectively, with a filter flow rate of 235 m^3/m^2 day (4.0 gpm/ft^2), producing an average effluent turbidity of 0.1 TU. Amphibole fiber count and mass removals were excellent with 4 out of 4 amphibole fiber counts and 4 out of 4 amphibole mass removals achieving the above stated removal goal. The economic analysis of this treatment process, based on a 30 mgd treatment plant design, is presented in Table 19 and shows that treated water could be produced for approximately 7.2 ¢/1000 gallons.

The second granular media filtration category selected utilized a tri-media filter bed with two-stage flash mixing at a filter flow rate of 293 m^3/m^2 day (5.0 gpm/ft^2). This category is represented by MM-2 Runs 93, 94, 103, 104, and 105. Alum and a nonionic polymer, 985N, were introduced at average rates of 11

TABLE 19. WATER TREATMENT PLANT ECONOMIC ANALYSIS – GRANULAR MEDIA FILTRATION 30 MGD PLANT DESIGN – LAKE SUPERIOR INTAKE AT LAKEWOOD

Process Category	Dual Media Bed $Q = 235\ m^3/m^2$ day Single Stage Mixing Alum & Nonionic Polymer	Tri-Media Bed $Q = 293\ m^3/m^2$ day Two-Stage Flash Mixing Alum & Nonionic Polymer	Tri-Media Bed $Q = 293\ m^3/m^2$ day In-Line Mixing Alum & Nonionic Polymer
	Actual Costs $\$x10^6$	Actual Costs $\$x10^6$	Actual Costs $\$x10^6$
Capital Costs			
First	5.50	5.25	5.25
Replacement-present worth of replacement equipment	0.66	0.63	0.63
Total-present worth of all capital costs, 50 year analysis at 5-5/8%	6.16	5.88	5.88
Average Annual Costs	$\$x10^6$	$\$x10^6$	$\$x10^6$
First	0.33	0.32	0.32
Replacement	0.04	0.04	0.04
O&M - calculated at 20 mgd	0.13	0.12	0.12
Total	0.50	0.48	0.48
Costs per 1000 gallons	¢/1000 gal	¢/1000 gal	¢/1000 gal
First	4.70	4.49	4.49
Replacement	0.60	0.57	0.57
O&M - calculated at 20 mgd	1.90	1.73	1.79
Total	7.20	6.79	6.85

and 0.03 mg/l, respectively, producing an average effluent of 0.1 TU. Amphibole fiber count and mass removals again were excellent, with the desired removal goals achieved for both the amphibole fiber count and mass removal. The economic analysis of this category of treatment, based on a 30 mgd treatment plant design, is presented in Table 19 and shows that treated water could be produced for approximately 6.79 ¢/1000 gallons.

The third granular media filtration category selected also utilized tri-media filtration at a filter flow rate of 293 m^3/m^2 day (5.0 gpm/ft^2) and is represented by MM-2 Runs 121, 122, and 123. Alum and a nonionic polymer, 985N, were introduced through a series of in-line mixers at rates of 12 and 0.05 mg/l, producing an average effluent turbidity of 0.06 TU. Amphibole fiber count and mass removals were excellent, with amphibole fiber count and amphibole mass removal achieving the desired goal for the single test performed. With a treatment plant designed for 30 mgd, treated water could be produced for approximately 6.85 ¢/1000 gallons as shown by the economic analysis presented in Table 19.

Diatomaceous Earth Filtration

Three categories of treatment also were selected for economic analysis from the runs utilizing pressure diatomaceous earth filtration. The selection of these categories had, as a common base, amphibole fiber count and mass removal to a level near or below the detectable limits of the analytical equipment and an average effluent turbidity of 0.1 TU or less. The three categories were the most economically attractive of the various categories screened, with average chemical and DE costs of 2.7, 2.3, and 2.9 ¢/1000 gallons, respectively, as compared to the range of average chemical costs for all pressure DE runs of 2.2 to 4.5 ¢/1000 gallons.

The first category selected utilized a medium grade DE precoat applied at 0.73 kg/m^2 (0.15 lb/ft^2) of filter surface area coated with alum and soda ash at rates of 0.11 g/g of DE and 0.055 g/g of DE, respectively. This category is represented by ERD-2 Runs 67, 68, and 69. A fine grade body feed was applied at a rate of 27.5 mg/l, with alum at 3 mg/l and soda ash at 1.5 mg/l added to the body feed. A filter rate of 61 m^3/m^2 day (1.04 gpm/ft^2) was utilized to produce an effluent with an average turbidity of 0.06 TU. Amphibole fiber count and mass removal achieved the removal goal in 2 out of 2 tests. The economic analysis of a treatment plant designed for 30 mgd and based on this treatment is presented in Table 20. The analyses indicate that a treated water could be produced for 11.97 ¢/1000 gallons.

TABLE 20. WATER TREATMENT PLANT ECONOMIC ANALYSIS – PRESSURE DIATOMACEOUS EARTH FILTRATION 30 MGD PLANT DESIGN – LAKE SUPERIOR INTAKE AT LAKEWOOD

Process Category	Q = 61 m^3/m^2 day Alum & Soda Ash to Precoat and Body Feed Fine Body Feed	Q = 67 m^3/m^2 day Alum & Soda Ash to Precoat-Cationic Polymer to Raw Water Fine Body Feed	Q = 64 m^3/m^2 day Alum & Soda Ash to Precoat-Cationic Polymer to Raw Water Medium Fine Body Feed
Capital Costs	Actual Costs $\$x10^6$	Actual Costs $\$x10^6$	Actual Costs $\$x10^6$
First	6.50	6.10	6.35
Replacement-present worth of replacement equipment	0.50	0.46	0.49
Total-present worth of all capital costs, 50 year analysis at 5-5/8%	7.00	6.56	6.84
Average Annual Costs	$\$x10^6$	$\$x10^6$	$\$x10^6$
First	0.39	0.37	0.38
Replacement	0.01	0.01	0.01
O&M - calculated at 20 mgd	0.43	0.39	0.44
Total	0.83	0.77	0.83
Cost per 1000 gallons	¢/1000 gal	¢/1000 gal	¢/1000 gal
First	5.43	5.09	5.30
Replacement	0.14	0.14	0.14
O&M - calculated at 20 mgd	6.40	5.80	6.56
Total	11.97	11.03	12.00

The second category utilized a medium grade DE precoat applied at 0.73 kg/m^2 (0.15 lb/ft^2) of filter surface area coated with alum and soda ash at rates of 0.11 g/g of DE and 0.055 g/g of DE, respectively. This category is represented by ERD-2 Runs 73, 74, and 75. A fine grade body feed was applied at a rate of 20.5 mg/l. A cationic polymer, Catfloc B, was added to the raw water at a rate of 0.56 mg/l. A finished water with an average effluent turbidity of 0.06 TU was produced. Amphibole fiber count and mass removals were excellent, achieving the removal goal in 2 out of 2 tests. The economic analysis presented in Table 20 shows that for this category a treated water could be produced for 11.03 ¢/1000 gallons.

The third category utilized a medium grade DE precoat applied at 0.73 kg/m^2 (0.15 lb/ft^2) coated with alum and soda ash at rates of 0.11 g/g and 0.055 g/g of DE, respectively. This category is represented by ERD-2 Runs 79, 80, and 81. A fine grade of body feed was applied at a rate of 27.3 mg/l. A cationic polymer, Catfloc B, was added to the raw water at a rate of 0.33 mg/l to produce a finished water with an average effluent turbidity of 0.06 TU. Amphibole fiber count and mass removals were excellent, achieving the removal goal in 2 out of 2 tests. The economic analysis presented in Table 20 shows that for this category treated water could be produced for approximately 12.0 ¢/1000 gallons.

Two other pressure DE categories with equally attractive chemical costs that were examined utilized only alum and soda ash applied to the precoat. These categories were represented by ERD Runs 59, 60, and 62 and ERD Runs 55, 57, and 58. Turbidity removal was not as successful, however, with average effluent turbidities in both categories greater than 0.1 TU.

A theoretical optimization was performed for the three selected pressure DE filtration categories to simulate the least cost performance for each process and the optimum design characteristics of the treatment plants in each case.[7] Pilot study data from the three runs involved in each of the three categories were utilized to predict the buildup of filter aid density for that category. From this value, values for the filtration rate, terminal head loss, body feed rate, filter area, optimum length of filter run, and the optimum filter operating costs were calculated. For each category, a filter flow rate of 94 m^3/m^2 day (1.6 gpm/ft^2) was predicted as compared to 60 m^3/m^2 (1.0 gpm/ft^2) utilized in the pilot studies. Body feed rates calculated were substantially lower than those actually run in the pilot studies, averaging between 5 and 10 mg/l as compared to 20 to 30 mg/l. Details on the DE optimization process are provided in Appendix I.

The optimization resulted in lower capital and average annual operation costs for all three of the selected categories. The costs in ¢/1000 gallons of treated water were optimized at 10.55, 8.50, and 8.14, respectively for the three categories, as compared to costs in ¢/1000 gallons of 11.97, 11.03, and 12.0 as determined from the actual pilot studies.

Application to Other Areas

Several less detailed cost comparisons were conducted to examine the capital cost differences between granular and pressure DE filtration for asbestiform fiber removal of plants of varying sizes. Ranges of cost for plant capacities of 0.03, 1.0, 10.0 and 30.0 mgd are presented in Table 21. The costs presented are construction costs only and do not include the costs of replacement equipment. A 25 per cent allowance for engineering, legal, administrative and contingency expenses has been included. The costs do not consider the many factors involved in a specific application, but are general costs that consider only filtration treatment for asbestiform fiber removal from water of the same general character as that utilized in the pilot plant study. Items such as existing equipment or facilities, existing distribution and storage systems, raw water quality, site location, and the need for pretreatment would modify the costs presented.

A detailed economic analysis was not conducted on any of the categories from the vacuum DE filtration runs as the treatment afforded by this process was not applicable to the Duluth raw water which was high in dissolved gases. The total pressure drop through the filter cake in vacuum DE filtration is limited to the total positive head of water above the filter plus the usable suction lift of the service pump of approximately 20 feet. Thus, the terminal head loss in the vacuum filter, 20 to 24 feet, would normally be at a pressure less than atmospheric, or at a negative head. The gas bubbles that are thus forced out of solution result in an air binding in the filter and either increase the head loss buildup or collapse the filter cake by creating cracks and allowing the turbidity to pass.[7] This problem was repeatedly encountered throughout the vacuum DE runs in the pilot studies. Attempts to stabilize the filter cake by increasing its thickness did not prevent the air binding of the filter and served only to increase the average chemical and DE costs per run to values 1.5 to 2 times more than the chemical and DE costs experienced in the pressure DE units.

An examination of the breakdown of the costs in terms of ¢/1000 gallons in Tables 19 and 20 indicates a wide variance in the percentage of operation and maintenance costs as compared to the total costs between granular media and pressure DE filtration. The O&M costs, composed of chemical, power, and labor costs, constitute approximately 25 per cent of the total costs for the granular media filtration as compared to approximately 53 per cent for the pressure DE filtration. This owuld mean that increases in O&M costs due to inflation would affect future costs in ¢/1000 gallons for pressure DE filtration more than granular media filtration.

The choice between pressure or vacuum DE filtration and granular media filtration would be dependent upon the specific application. Several factors,such as quality of raw water and quantity of water to be treated, would have to be examined before a definite selection could be made. In the case of a treatment plant at Duluth designed for 30 mgd and utilizing Lake Superior water at the Duluth Lakewood Intake, the choice can be made based on the economic evaluation presented. However, the choice of treatment plants for very small capacity installations utilizing water with different quality parameters would require a detailed study of the specific conditions at each potential site.

TABLE 21. RANGES OF INITIAL CAPITAL COSTS OF VARIOUS PLANT CAPACITIES UTILIZING GRANULAR MEDIA AND PRESSURE DE FILTRATION FOR ASBESTIFORM FIBER REMOVAL[a]

Process	Plant Capacity (mgd)			
	0.03 $\$x10^6$	1.0 $\$x10^6$	10.0 $\$x10^6$	30.0 $\$x10^6$
Granular Media	0.04-0.05	0.19-0.24	2.9-3.4	5.2-5.5
Pressure DE	0.05-0.06	0.22-0.25	3.1-3.5	6.1-6.5

[a] Costs presented do not consider replacement costs or costs associated with pretreatment. Items such as existing equipment or facilities, existing distribution and storage, raw water quality, and site location would modify the general cost ranges presented.

MONITORING PLANT OPERATION

Purpose of Monitoring

It is customary to monitor the quality of drinking water after it is treated by a water utility. This is done for a number of reasons, including assuring both the consumers and regulatory authorities that the water meet appropriate standards, and assuring utility operators and managers that the treatment plant is being operated properly and that the goals of the treatment processes are being achieved.

Monitoring techniques vary. The efficacy of clarification can be monitored by measuring turbidity. Waters are disinfected to kill pathogenic microorganisms, but judgments on the achievement of this goal are made on the basis of the presence or absence of indicator microorganisms, along with measurements of turbidity and chlorine residual, rather than on specific tests for pathogens.

Because at the present time there is no rapid analytical method for detection of asbestiform fibers in water, treatment plant operators shall have to rely on indicators and the use of proper operational procedures to assure the production of water low in asbestiform fiber content, just as operators now rely on indicators for pathogens.

Effluent Turbidity

One treatment goal that should aid in the production of water with amphibole fibers present in low quantities is the attainment of an effluent turbidity at or below 0.1 TU. Turbidity is not a direct measure of amphibole fiber count in water, but Figure 24 shows that high amphibole fiber counts were more likely to occur when effluent turbidities exceeded 0.2 TU. Filters should be backwashed when the effluent turbidity rises to 0.2 TU. For chrysotile, however, there did not appear to be any relationship between effluent turbidity and fiber count. High fiber counts occurred with both high and low effluent turbidities, as shown on Figures 24 to 29. This relationship was demonstrated for certain types of filters and processes treating Lake Superior water. It should not be assumed to hold true in other parts of the country until demonstrated so by experimentation.

X-Ray Analysis for Amphibole Mass

Even though an effluent turbidity goal can be stated, it is highly desirable that some monitoring capability exists, so that an operator can verify that following established procedures actually does cause the reduction of asbestiform fiber count. Ultimate proof of this now is obtained by electron microscope analysis of water samples, a costly and time-consuming technique. To assure that amphibole fibers are being removed, a type of indicator test, X-ray diffraction analysis can be performed. This method gives results in terms of milligrams of amphibole mass per liter of water, and it is quite useful.

The amphibole mass tests done at NWQL for this research were used as a guide to planning further filtration research, because of the time delay involved in getting back electron microscope results. In addition, the amphibole mass data provided independent verification of the ability of filters to remove amphibole fibers.

The performance of the four filtration processes as measured by amphibole mass analysis is presented in Table 22.

TABLE 22. SUMMARY OF NWQL RESULTS

Process	Total No. Of Samples Submitted	No. of samples with measurable Amphibole conc. and/or detection limit ≤0.005 mg/l	No. of samples with amphibole conc. ≤0.005 mg/l
Dual Media	32	24	22
Mixed Media	24	24	23
Vacuum DE	29	21	17
Pressure DE	27	25	23

Data in this table are presented in three categories because the detection limit of the X-ray method varied, depending in large measure on the volume of water filtered. This in turn was a function of the suspended solids content of the water, with higher quantities of suspended solids plugging the membrane filter sooner, resulting in higher detection limits. Thus we are concerned not only with how many samples were submitted for X-ray analysis, but also with the number of samples to which a definite amphibole mass concentration could be assigned, or which had an amphibole mass concentration ≤0.005 mg/l. Finally, the number of filtered samples having ≤0.005 mg/l amphibole mass are tabulated.

In general, each process performed reasonably well for amphibole removal. However, the vacuum filtration process failed to achieve ≤0.005 mg/l in the filtrate in four instances vs. one or two for the other processes.

Amphibole Mass vs. Fiber Count - Filtered Water

The amphibole mass X-ray analysis was the principal analytical method relied upon for making week-to-week operating decisions during the filtration research. In addition, it has provided independent verification of the capability of filtration processes to remove amphibole fibers. Finally, X-ray analysis offers the operator of a municipal filtration plant the opportunity to monitor for amphibole removal at a cost much lower than electron microscope analysis.

It can be shown statistically that X-ray analysis is useful for monitoring in place of electron microscope testing. In analysis of data from this research, a desired goal for amphibole fibers in filtered water was $\leq 0.04 \times 10^6$ f/l. A desired goal for amphibole mass was ≤ 0.005 mg/l. One can ask to what extent the desired goals were simultaneously either attained or not attained. If $\leq 0.04 \times 10^6$ f/l and ≤ 0.005 mg/l generally tend to be observed together in filtered water, then X-ray analysis would be a valuable tool for monitoring filter effluent.

In order to do such a statistical analysis, it is necessary first to pair data from NWQL and ORF. The NWQL X-ray data had a varying detection limit, because of the suspended solids in water filtered for analysis. It is necessary to know if amphibole mass exceeds 0.005 mg/l, so for samples with amphibole mass expressed as an indefinite value below a detection limit, the data could be considered only if the detection limit was 0.005 mg/l or less. For example, a value expressed as 0.01 mg/l could be greater than or less than 0.005 mg/l, so such data would have to be omitted in this analysis. Data are grouped according to filtration process, not unit, and the only runs not included in the statistical analysis are those rejected because of the high amphibole mass detection limit.

The results are presented in Table 23.

TABLE 23. COMPARISON OF AMPHIBOLE MASS AND EM RESULTS IN FILTERED WATER SAMPLES

Process	Pairs of data amphibole mass known to be above or below 0.005 mg/l	Pairs of data with simultaneous occurrence of 0.04×10^6 f/l and 0.005 mg/l or $\leq 0.04 \times 10^6$ f/l and ≤ 0.005 mg/l
Granular Dual Media	23	20
Granular Mixed Media	23	23
Pressure DE	24	18
Vacuum DE	21	14

Since the simultaneous attainment of the selected values occurred in all but three data pairs for dual media filtration and for every data pair for mixed media filtration, analysis was made on the basis of probability rather than by using a chi-square table. For each process, the hypothesis was made that there is no relationship between EM and X-ray data. Thus the probability for simultaneous occurrence of high or low values becomes 0.5, and the significance of the experimental results can be tested. At the 99 per cent confidence level, simultaneous occurrences of high or low EM and X-ray values was significantly greater than one would expect for random events for dual media, mixed media, and pressure DE filtration. The difference was not statistically greater for vacuum DE data.

On the basis of the analysis of the probability of the observed events, it can be stated that for dual and mixed media granular filtration and for pressure DE filtration, the X-ray amphibole mass analysis can be used to indicate if the amphibole fiber count of the filtered water would be equal to or less than a count of 0.04 x 10^6 f/l by ORF. Although amphibole mass should not be used as an indicator for chrysotile, the X-ray analysis is faster and cheaper than EM analysis and it is a useful indicator method for monitoring water for amphibole fibers.

Suspended Solids Data - NWQL

The difference in performance between the vacuum filtration process and the other processes can be related in part to the inability of the vacuum filter unit to prevent the passage of DE through the septum. In the suspended solids data reported by NWQL, there is often a footnote beside the BIF (vacuum DE) data stating that the solids were mostly DE. This judgment was based upon visual and optical microscope observations.

It can be demonstrated statistically, by comparing mean filtered suspended solids, that the vacuum filtration process was not as effective for removing suspended solids. For purposes of this comparison, data are grouped by process, so that dual media filtration includes data from MM-1 and MM-2. In order to assess the capabilities of the processes, early runs involving less successful techniques were excluded. Thus in dual media filtration data, runs involving alum and anionic polymer and all ferric chloride runs are deleted. In the mixed media data, a run deliberately sampled after turbidity breakthrough was deleted. All single precoat step runs and all runs involving conditioning with 575 C polymer were deleted from ERD and BIF data. The results are presented in Table 24.

TABLE 24. SUSPENDED SOLIDS IN FILTRATE

Process	No. of Samples	Mean Suspended Solids mg/l	Standard Deviation	Significantly different from BIF @ 99% Confidence Level
Granular Dual Media	28	0.084	0.066	Yes
Granular Mixed Media	23	0.067	0.040	Yes
Pressure DE	20	0.079	0.146	Yes
Vacuum DE	20	0.408	0.190	–

It is evident that the mean suspended solids from the granular filtration and the pressure DE processes were considerably lower than the solids from the vacuum DE filter, and these differences were statistically significant. This is additional evidence that the vacuum filtration process experienced operating problems throughout the testing period, at least in part because of bubble formation in the DE, a problem brought about by low water temperatures and the saturation of the raw water with dissolved gases.

Efforts to Develop Rapid Detection Methods

A limited effort to learn about rapid detection of asbestiform fibers was made in this research, but the principal objective was to learn about fiber removal by filtration. Other efforts to develop a rapid fiber detection method are underway, sponsored by EPA and other Federal agencies. One method being investigated involves placing a water sample in a laser light beam measuring scattered light from incident angles of about 10° and 135° and relating variations of light intensity and incidence angle to the types of particles present in water. One of the goals of these efforts is to provide a technique that is practical for monitoring both amphibole and chrysotile asbestiform fibers in water at filtration plants. Such a technique should be rapid enough to permit a plant operator to make meaningful changes in the treatment process in order to hold fiber content of the filtered water to a minimum. Until a more rapid method is available, water filtration plants on Lake Superior should use the X-ray diffraction method, along with occasional EM analyses.

FUTURE RESEARCH

Information developed in this pilot plant research permits a number of questions to be formulated for future study. Among the ideas that could be investigated are the following:

1. Ways to improve chrysotile removal by anionic polymer conditioning of DE or by the use of three-stage mixing and combinations of three conditioning chemicals in granular filtration.

2. Effect of high algal counts on filter performance.

3. Fiber removal during times of highest amphibole mass and fiber count.

4. Verification of POPO optimization.

5. Additional filtration experiments at 5 to 6 gpm/ft^2 with granular filters.

6. Effect of mixing intensity on filtration, and a comparison of back-mixing vs. in-line mixing.

7. Further laboratory development, followed by pilot plant tests, of an operator's method for monitoring the presence of asbestiform fibers in water.

A number of the suggestions for future work represent an extension of past work into promising study areas. Additional research is needed to increase the knowledge of the water treatment profession on the topic of asbestiform fiber removal by filtration.

SECTION VIII

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SECTION IX

GLOSSARY

alum – aluminum sulfate

B.W. -- backwash

BDL – below detectable limits

BIF – vacuum diatomaceous earth filtration unit

cm – centimeter

m^3 – cubic meter

m^3/m^2 day – cubic meters per square meter day

°C – degree Centigrade

°F – degree Fahrenheit

DE – diatomaceous earth

DO – dissolved oxygen

\$/1000 gal – dollars per 1000 gallons of treated water

EPA – Environmental Protection Agency, U. S.

ERD – pressure diatomaceous earth filtration units

ERD-1 – standby ERD unit

ERD-2 – main ERD unit

$FeCl_3$ – ferric chloride

f/l – fibers per liter

ft – foot

gal – gallon

gpm – gallons per minute

gpm/ft^2 – gallons per minute per square foot

g – gram

g/g DE – grams per gram of diatomaceous earth

H_L – head loss

hp – horsepower

in – inch

kg – kilogram

kg/hr – kilograms per hour

kg/m^2 – kilograms per square meter

m – meter

μm – micrometer

mph – miles per hour

mg – milligram

mg/l – milligrams per liter

ml – milliliter

MGD – million gallons per day

MM-1 – granular media filtration unit designated No. 1

MM-2 – granular media filtration unit designated No. 2

min – minute

NWQL – National Water Quality Laboratory

ORF – Ontario Research Foundation

lb – pound

lb/hr – pounds per hour

lb/ft^2 – pounds per square foot

psi – pounds per square inch

lb/1000 gal – pounds per 1000 gallons

rpm – revolutions per minute

soda ash – partly purified sodium carbonate

cm^2/g – square centimeters per gram

ft^2 – square foot

m^2 – square meter

SS – suspended solids

TU – turbidity unit

UMD – University of Minnesota at Duluth, School of Medicine

w/o – without

yr – year

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